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**Response to organic and inorganic fertilization, model
development and evaluation for Napier grass (*Pennisetum
purpureum*, Schum.)**

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1.1 Introduction

Napier grass (*Pennisetum purpureum*, Schum.) is a C₄ grass species originally from eastern and central Africa (Boonman, 1993). Its versatility promoted its wide distribution in tropical and subtropical areas of the world. This pasture is one of the most used to feed different species of animals such as cattle, goat, sheep, pig, horses, and guinea pig. It is even cultivated as barrier to control soil erosion (Owino and Gretzmacher, 2002), for paper pulp fibre (Ferraris and Sinclair, 1980), a source of renewable energy (Woodard *et al.*, 1993), and to feed some species of fish (Chikafumbwa, 1996). Its high potential productivity and adaptability to a broad range of climatic and soil characteristics explains its current wide distribution and utilisation as forage, from sea level up to an altitude of 2000 m.a.s.l. (Van de Wouw *et al.* 1999).

Its wide distribution around the world and the existence of more than 53 accessions number of Napier grass (Van de wouw *et al.*, 1999) has promoted a lot of research, which has focused on its agronomic characteristics, chemical composition, and animal performance. However, a simulation model for “cut and carry” systems has yet to be developed, to facilitate predictions based on physiological responses with the integration of external factors such as soil, climate and management.

In South America, Brazil was the first country in which Napier grass was introduced in around 1920. In the 60's farmers began to use it in “cut and carry” systems, and 10 years later some institutions promoted its utilization through grazing (De Faria *et al.*, 1998). In the tropical area of Bolivia, Napier grass has been grown since the 70's. Its distribution has increased in the last 10 years, and it is now used exclusively in “cut and carry” systems. A survey carried out in 1997, which involved more than six thousand farmers from the dairy basin of Santa Cruz, determined that around 25% of the farms used Napier grass as a feed resource (Herrero *et al.* 2000).

1.2 Napier grass: origin, morphology, agronomic and nutritive characteristics

Napier grass (*Pennisetum purpureum* Schum.), also known as Elephant grass, is a perennial pasture native to eastern and central Africa. It has its centre of diversity in the surroundings of rain forest margins and river beds, where the soils are characterized by high fertility. Its common name was adopted from Colonel Napier, who introduced the species to Zimbabwe to study its characteristics and use in commercial livestock production (Boonman, 1993).

Napier grass is a very large, robust, tufted, perennial member of the subfamily Panicoideae, tribe Paniceae. It produces culms 2 – 7 m tall with leaf blades up to 90 cm long, and 3 – 5 cm wide, pilose near the base, and on its margins the blade is rough. Its inflorescence is a compact, cylindrical spike up to 30 cm long (Bogdan, 1977; Jones, 1985).

According to its agronomic characteristics, Napier grass may adapt to different soil types, but grows better in deep soils with moderate to heavy texture. It tolerates short droughts and high moisture level, but not floods lasting for more than 3 days. The optimum temperature for its growth is 33/28°C of day/night temperature (Ferraris *et al.*, 1986). The seed is unfertile and this grass has to be propagated vegetatively by root crown division or rhizome and mature stem fragments.

In the cut and carry utilization, the cut interval is the most important factor to define protein concentration, digestibility, and biomass production. For example, Andrade and Gomide (1971), advise to cut Napier grass when the plant is between 1.5 to 1.8 m high, a height that may require a 50 to 90 days growth. This recommendation is in agreement with Cosser *et al.* (1996), who determined that the best height to use the plant is at 1.7 m. For the Kenyan dairy system, Kariuki *et al.* (1998) defined the cutting plant height from 0.5 to 1 m, which is coincident with Werner *et al.* (1965), who consider that it is better to cut when the plant has reached 0.7 to 0.8 m height rather than 0.3 to 0.4.

1.3 Temperature and photosynthesis

Temperature is one of the most important factors determining plant growth, development and yield. Knowledge of plant temperature response is thus a prerequisite to successful crop systems, modelling and application of such models to management (Weikai and Hunt, 1999). According to Jones (1985), Napier grass is affected by the seasonal temperature variation throughout the year because its performance not only depends on the moisture availability but also on the climatic factors, particularly the temperature.

For several tropical C₄ grasses grown at 30°C, the minimum temperature for net photosynthesis is 5 – 10°C, the optimum temperature is 35 – 40°C, and the maximum temperature at which net photosynthesis is positive is 50 – 60°C. In Napier grass the minimum, optimum, and maximum temperature for positive net photosynthesis were 6.7, 36.7, and 58.8°C, respectively (Ludlow and Wilson, 1971). The optimum temperature is higher than the one found by Ferraris *et al.* (1986), who determined that the optimum day/night temperature for Napier grass growth is at 33/28°C, meaning the highest photosynthesis rate is at 33°C. However, these values are similar to the rank of values found by Vong and Murata (1977) for some tropical C₄ grasses, which showed the best net photosynthesis at temperatures ranging from 30 to 36°C. According to Ferraris *et al.* (1986), the response of leaf appearance to temperature resulted in increased leaf area and leaf weight per plant, and it was independent of radiation level. Therefore, the results of radiation showed light differences between spring and summer (56.25, and 55.95 MJ m² day⁻¹) when compared to autumn (46.51 MJ m² day⁻¹).

1.4 Response to fertilization and yield

Pasture degradation is linked to an inadequate management (Jones and Jones, 1997), leading in the medium and long term to soil nutrient depletion and lack of regeneration capacity of the introduced forage plants. Though pasture degradation is normally detected after a few years (Macedo, 1997), it mostly originates from incorrect management practices leading to changes in the dynamics of the pasture in the short

term. Nitrogen is the factor that frequently limits the pasture production, because the natural nitrogen in the assimilate stage is much less than 2% (Whitehead, 1995).

Crude protein content is especially sensitive to nitrogen fertilisation, increasing linearly with fertilizations from 0 to 150 kg N ha⁻¹ year⁻¹ (Alvim *et al.* 1990). However, there are variations in the response to nitrogen fertilization according to the pasture species, and its potential productivity.

In Napier grass it is feasible to apply doses higher than 150 kg N ha⁻¹ year⁻¹. For example, Vicente-Chandler *et al.* (1959), applied different levels of N fertilization (224, 448, 896, 1344, and 2240 kg N ha⁻¹) in Napier grass cut at 60 days, and determined N use efficiency of 47, 54, 37, 26, and 16 kg DM per each kg of N applied, respectively. This result is according to the recommendations made by Trillas (1982), who proposed that the best user efficiency by tropical and subtropical pastures is obtained with N doses from 300 to 400 kg N ha⁻¹ year⁻¹. Therefore, using lower doses result in poorer responses. An example of this concept are the results obtained by Saraiva and Carvalho (1991), who applied a maximum dose of 120 kg N ha⁻¹ year⁻¹, and obtained only a 3.5% increase of biomass production. Cumulative dry matter yield of Napier grass is variable, depending of the region, soil, climate and management.

Forage yield is referred to biomass production, which normally is expressed as dry matter (DM), and means the solid fraction of forage remaining after eliminating the moisture contained in the material. Blater and Wilson (1963) define pasture productivity as the result of climatic factors, which are dependent on the seasonal distribution of precipitation and the high temperatures. So, this grass species shows a wide variation in its performance and biomass production for forage may range from 10 to 40 tonnes per hectare per year (Mwakha, 1972; Skerman and Cameron, 1990; Schreuder *et al.* 1993; Boonman, 1993; Anindo and Potter, 1994; Humphreys, 1994; Wouters, 1997; Macoon, *et al.*, 2002). An explanation of these yield variation could be in the wide range of varieties of *Pennisetum purpureum* distributed throughout de tropic and sub-tropic of the world.

In addition, many studies concluded that the performance of Napier grass is dependent not only on the climatic and soil conditions, but also on the management

(Costas and Chadler, 1961; Ferraris and Sinclair, 1980; Ferraris *et al.*, 1986; Kubota *et al.*, 1994; Andrade *et al.*, 2000; Tudsri *et al.*, 2002). For agro-industrial use (energy production), Ferraris and Stewart (1979) applying three months cutting intervals in Napier grass, harvested an accumulative production of 69.5 tonnes DM year⁻¹, corresponding 67.8% to stem rate.

1.5 Chemical composition and digestibility

The protein concentration in grass tissue varies with age and between plant structures. Also biomass production and leaf proportion is dependent on the pasture growth stage. Therefore, whilst the age of the plant increases, the leaf proportion and protein concentration decreases (Jones, 1985; Britto *et al.*, 1966). Ferrari and Lavezzo (2001) applied 100 kg N ha⁻¹ and cut when the pasture was 70 days of age, obtaining 7.71%, and 71.88% protein and NDF, respectively.

Kariuki *et al.* (1998) at a cutting age of 52 days found values of 57.1%, 11.8% and 58.7% for digestibility, protein and NDF, respectively. For Nyambati *et al.* (2003), using Napier grass in mature condition found values of 6.84 and 71.2% for protein and NDF, respectively. According these two cited references, the plant age definitively influences the composition of the forage. However, the literature shows the use of criteria to evaluate the Napier grass performance, some cases it is based in plant age and another in plant height.

Taking plant height as the variable to characterize this crop, Zewdu *et al.* (2002), at different inorganic fertilizer level and three plant cutting height (0.5, 1 and 1.5 m), the *in vitro* dry matter digestibility ranged from 61.03 to 71.74% as cutting plant height increased from 0.5 to 1.5 m.

Considering the age as reference to cut the plant, Vieira *et al.* (1997), cut at ages of 61, 82, 103, 124 and 145 days, and found protein values of 16, 13.3, 8.8, 7.6, and 6.8 %. For NDF the values were 58.3, 61.9, 68.9, 69.7, and 73.4, respectively. Kozloski *et al.* (2005), measured Napier grass (cv. Mott) at 30, 50, 70 and 90 days, and determined values for NDF of 65.6, 65, 65, and 61%. Using the same grass variety, Sarwar *et al.*

(1999) assessed protein, NDF and *in situ* biomass digestibility at two cutting ages (40 and 60 days), and two fertilizer treatments, with and without nitrogen fertilizer. The results for protein increase from 8.6 to 12.7% at 40 days and from 7.1 to 10.8 at 60 days of cutting age. For NDF analysis, the values increase from 70.6 to 73.6% for 40 days and from 78.3 to 79.1% for 60 days of cutting age. The biomass digestibility increases from 54.2 to 61.5% for 40 days and from 50.7 to 48.8% for 60 days of cutting age.

From the point of view of carbohydrates concentration, Vilela (1990) suggests that Napier grass should be cut for silage, when the pasture is 60 to 90 days of age. Reed *et al.* (2000) evaluated total non-structural carbohydrate (TNC) and nitrogen (N) concentration in leaf blade, leaf sheath, stem base and stem top, cutting every three days from 3 to 36 days, and found mean values of 149.5, 201.8, 231.8 and 261 g kg⁻¹ DM for TNC, and 24.3, 12.3, 5.9, and 5.5 g kg⁻¹ of N, respectively.

Anyway, it is necessary to clarify that according to the references the quality of the forage will be mainly dependent on function of plant age, because maturity is considered to be the primary factor affecting the chemical composition and nutritional quality of most forages (Nelson and Moser, 1994).

1.6 Intake and milk production

For Napier grass, in cut and carry systems and chopped before feeding, Anindo and Potter (1986) determined a forage average intake of 3.16 and 2.63 kg DM day⁻¹ per 100 kg bodyweight, for unsupplemented and supplemented treatments, respectively. Under these feeding conditions, the mean milk production along the experiment was 10.5 and 15 kg day⁻¹. The level of 10.5 kg milk cow⁻¹ obtained from the forage only diet in this experiment was about twice the level reported as the national average from grade cows in Kenya (Stotz, 1983). However, the result (10.5 kg milk cow⁻¹day⁻¹) determined by Anindo and Potter (1986) in the stalls system is similar to that reported (11.4 kg cow⁻¹day⁻¹) by Aroeira *et al.* (1999), but in a grazing system with Napier grass at 30, 37.5, and 45 days of age. Olivo *et al.* (1989) during the rainy season and in a grazing system obtained an average of 9.8 kg milk cow⁻¹ day⁻¹. On the other hand, averages of milk production from 10000 and 15000 kg ha⁻¹ were reported by Deresz (1994) and Coser *et*

al. (1996) with crossbred cows grazing Napier grass during the 180 days of rainy season. However, the breeding cows are a factor which could influence the milk production response, for example, Muinga *et al.* (1993) feeding Jersey cows with Napier grass with and without protein concentrate got milk production of 6.4 and 4.2 kg day⁻¹ cow⁻¹ respectively. This is similar with the results obtained in smallholders dairy systems by Joaquin *et al.* (2004) giving pure Napier grass fodder to crossbred cows (Brown Swiss – Cebu/Creole), which mean was 5 kg cow⁻¹ day⁻¹.

1.7 The grass role in the agriculture

The last three decades in Southeast Asia, especially in Thailand and Malaysia, forage research has also focused on small-scale commercial cattle fattening systems (commonly based on heavily fertilised *Pennisetum Purpureum* pastures) and smallholder dairy production. So, the governments have focused forages programmes on productive grasses (Stür *et al.*, 2002). In the upland of the Philippines the agriculture is becoming unsustainable, because of soil erosion and productivity of crops is limited by poor soils, and therefore livestock production has become a particularly valuable source of income to complement crop production. Under these circumstances, the incorporation of Napier grass as a dual-purpose resource (forage and hedgerow) has been used (Lapar and Ehui, 2003). A survey in the South of Indonesian indicates that Napier grass is present in 88% of the farms, which resource is used to feed dairy cows (Parikesit *et al.*, 2005). Many studies of agricultural systems and forage research demonstrate that Napier grass is the main resource to feed dairy cows in the Central area of Kenya (Kariuki *et al.*, 1998; Muia *et al.*, 1999; Mwangi, 1999; Lekasi *et al.*, 2001; Owino and Gretzmacher, 2002; Nyambati, *et al.*, 2003). Its milking basin is constituted by smallholder dairy systems with a diversification of crop production in a small land area where the forage production is based on Napier grass and the residual plant, maize. In the Southeast of Brazil, Napier grass is widely used either cut and carry system (silage) or grazing (Vilela, 1990; Coser *et al.*, 1996; De Faria *et al.*, 1998; Almeida *et al.*, 2000). Grazing is Napier grass most common use and they apply high stocking rate and short grazing period to avoid trampling, however, this system is supported by an inorganic fertilizer program (Saraiva and Carvalho, 1991). In Bolivia,

this grass is distributed in the dairy basin of Santa Cruz de la Sierra, where the number of farmers producing milk is over 7000. In 1997, a survey determined that Napier grass distribution was over 25% (Bernues *et al.*, 1998), however, the proportion of farmers using this grass eight years later had increased, as result of land use forced by other commercial crops, especially Sugar cane.

The dissertation objective

The objective of this thesis is to characterise Napier grass growth using different fertilizer levels and ages, and to adapt a model for the grass, with the aim of generating better understanding in crop management.

Structure of the thesis

Thesis can be divided in three main parts:

The first part (Chapters 1, 2 and 3) corresponds to the Napier grass review and the resume of the two experiments: Napier and Manure fertilization and Interaction between temperature and nitrogen fertilization. The second part (Chapters 4 and 5) comprises of the Calibration of the Napier grass model (based in the third experiment) and the evaluation model (using the second experimental data). The last part (chapter 6) evaluates the information obtained from the experiments and the developed model.

In detail:

Chapter 1: includes a review about Napier grass.

Chapter 2: describes the pasture response to manure fertilization and three cut frequencies. Variables related to manure and plant dynamics were assessed in repeated measurement method.

Chapter 3: describes the effects of nitrogen and temperature on morphologic and structural variables of leaves and tillers of Napier grass grown in the field, with irrigations according to requirements. Measurements were taken in two cut intervals

applying repeated measurement method.

Chapter 4: describes the Napier grass Model calibration adapted to the CROPGRO - DSSAT program.

Chapter 5: describes the Napier grass Model evaluation.

Chapter 6: correspond to general discussion

Abstract

Napier grass (*Pennisetum purpureum*, Schum.) is one of the forages with high potential for dairy systems in tropical areas. However, farmers using this grass usually report a decrease in soil fertility and fast grass maturation, effects that reduce its advantages. These problems support the need for detailed information on the interaction between Napier grass growth, development and crop management. The goal of this study was to determine the growth dynamics, sward structure and forage quality of Napier grass under different levels of manure fertilization and cutting frequencies in Bolivia. The characteristics of Napier grass pastures were evaluated in a period of 180 days during summer and autumn. The main treatments consisted in the application of manure at rates of 0, 15, 30 and 60 t DM ha⁻¹. Aboveground biomass was measured at three different cutting intervals: 30, 45 and 60-days, resulting in six, four and three cuttings, respectively. The 60-days cutting interval had the best performance for total biomass production. The biomass production, as a function of the three fertilizer treatments (15, 30 and 60 t ha⁻¹ of manure), was 354, 405 and 381 kg DM per ton of applied manure. Plant structural and morphological variables showed significant differences ($p<0.01$ and $p<0.05$) between treatments. It can be concluded from this study that Napier grass crop response to manure fertilizer shows that manure recycling could be a strategy technically and economically viable to produce forage while maintaining the soil fertility.

2.1 Introduction

Most of the tropical agricultural production systems have a negative nutrient balance. So, the tropical area of Bolivia has a common problem with other developing countries in that nutrients are being removed from the soil by crops and pastures, while not being replaced with inorganic fertilizers, because farmers cannot afford the high costs of inorganic fertilizers (Joaquin *et al.*, 2002). Most milk in the

dairy basin of Santa Cruz is produced by medium and smallholder dairy systems, which rely on pastures as the main feeding resource for milk production (Herrero *et al.*, 2000). In intensive dairy systems, farmers use a high level of feed supplement to cover the forage deficit. Low voluntary intake of forage during grazing, poor quality of forage, and non-existent fertilizer applications affect the majority of smallholder milk production systems. Consequently the mean milk production is less than 3.5 kg cow⁻¹ in these intensive dairy systems (Joaquin and Herrero, 2001).

Napier grass has a great potential to produce large quantities of forage. Recently this forage was introduced in tropical and sub-tropical regions around the world (Machado *et al.*, 1996, Muia *et al.*, 1999; Mwangi, 1999, Deschamps and Brito, 2001). However, despite its value as a forage crop, it is considered to have high nutrient requirements, and this may limit its adoption among farmers. In the current study area, around 30% of the farmers use Napier grass in “cut and carry” methods. However, most of the farmers did not understand the importance of considering a specific cutting interval and fertilisation for efficient management of Napier.

Organic manures contain valuable quantities of nitrogen, phosphate and potash, but many farmers regard them as waste materials rather than as a source for plant nutrients (Smith and Chambers, 1993). In African farming systems, the role of manure is fundamental, not only for Napier grass, but also for annual crops (Stoorvogel and Smaling, 1990). For example, Mwangi (1999) after applying 8 t of manure (74 kg N) to Napier grass with a cutting interval of 60 days, observed an increase in biomass of 18.4 kg per kg of N contained in manure when compared to the control treatment. Yet this represented adequate nitrogen to have an impact only on the first growth stage of Napier grass. However, according to Boonman (1997), manure is a more efficient system for recycling phosphorus and potassium rather than nitrogen, because manure is low in nitrogen and therefore it has been necessary to be applied at high quantities per unit land area.

In the study area, improving forage availability and soil fertility could increase forage intake by cattle during both the rainy and dry seasons, and consequently improve or negate the forage deficit during the dry season. All milk production systems in this study area had the possibility to improve forage quality and quantity

by including Napier grass, fertilized with manure, as a component of the system. By improving forage intake, cattle performance, milk production and family income would also be expected to improve. Therefore, the goal of this study was to determine whether animal manure could be an important resource for improving forage availability and maintaining soil fertility in milk production systems of tropical and sub tropical ecosystems. The specific objective of this study was to assess both the response of a Napier pasture to different manure fertilization levels and cutting frequencies.

2.2 Materials and Methods

2.2.1 Site and climatic characteristics

The experiment was conducted at the San Marcos farm, Santa Cruz, Bolivia (17° 14'S; 63° 10'W; 320 m.a.s.l.). Weather data were obtained from a meteorological station located 10 km from the experimental site. The climate of the area is tropical with two marked seasons of similar duration: a hot rainy summer from October to March and a dry winter from April to September. The mean temperature for the last 47 years showed that the coolest months are June and July (average daily temperature of 20.2°C) and the hottest months are December and January (25.8°C). The annual mean precipitation is 1365 mm, the wettest month is January (224 mm) and the driest is July (42 mm) (Busqué and Herrero, 2001). During the experimental period, the mean temperature was 25.4 °C and precipitation 738 mm (Figure 2.1).

2.2.2 Pasture and crop management

The total experimental area comprised 432m² of six-year-old Napier grass and the experimental period had duration of 180 days. Management of the pasture prior to the experiment consisted of manure application once a year, irrigation during the dry season and harvesting using the cut and carry method. There was no residual manure in the experimental area at the beginning of the study. Plant density was based on the established crop: one plant m⁻². The area was divided into 36 plots, measuring 4 x 3 m, each containing 12 plants. Two plants per plot were monitored. The experiment consisted of four different manure treatments (0, 15, 30 and 60 t of DM ha⁻¹) and

three cutting intervals (30, 45 and 60-days). There were three replicates for each manure treatment (Figure 2.2). The experimental design was a randomized split-plot complete block design, in which manure fertilization was the main factor and cutting interval was the split factor.

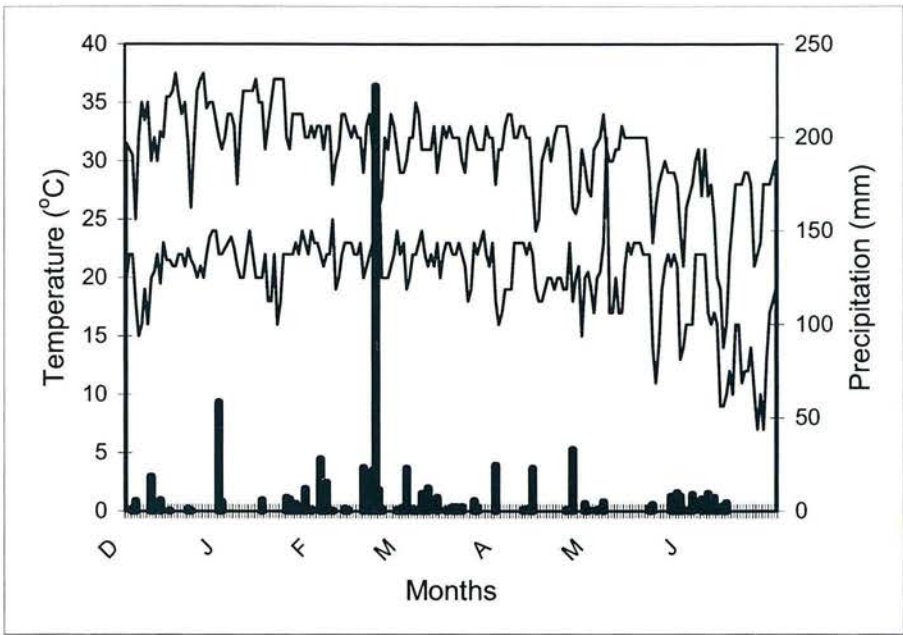


Figure 2.1. Minimum and maximum mean daily temperature (lines and left vertical axis) and precipitation (columns and right vertical axis) for the experimental site from December 2001 to June 2002.



Figure 2.2. Plot with manure fertilizer in Napier grass at 60 tonnes dry matter ha⁻¹

2.2.3 Soil characterisation

The physical and chemical characteristics of the soil were analysed at the start of the experiment. Randomised samples at a depth of 20 cm were collected around and between plants. The mean concentrations of nitrogen and organic matter were 0.14% (± 0.02) and 2.1% (± 0.59), respectively. Thus, the carbon–nitrogen ratio was 6:1. To assess nitrogen and organic matter at the end of the experiment, soil samples were extracted from each monitored plant at a depth of 20 cm after all residual applied manure had been removed.

2.2.4 Manure characterization

The manure used in the experiment had been stored for around 60 days without protection from the environment. Doses of manure application were transformed into kg of dry matter $\text{plant}^{-1} \text{m}^{-2}$. Before the start of the experiment, the concentration of nitrogen, organic matter and dry matter of the manure were determined. The mean values were, respectively, 1.8% (± 0.1), 64.78% (± 3.55), and 24.3% (± 0.7). The individual doses of manure per plant were 1.5 kg of DM for the $15 \text{ t ha}^{-1} \text{y}^{-1}$ treatment; 3 kg DM for the $30 \text{ t ha}^{-1} \text{y}^{-1}$ treatment; and 6 kg of dry matter for the $60 \text{ t ha}^{-1} \text{y}^{-1}$ treatment. Each dose was weighed and applied per individual plant using separate bags. The gradual change in nitrogen and organic matter of the manure that was applied was monitored through samples that were collected every 30 days. At the end of the experiment all the residual manure that remained around each individual plant was collected and weighed, and a sub-sample was taken to assess dry matter, nitrogen and organic matter content. Thus, the rate of nutrient loss throughout the experiment in relation to treatment regime and cutting interval could be analyzed.

In addition, an assessment was made of the changes in nitrogen concentration in manure from the moment of production until 45 days of storage. The study was conducted based on local management, where manure is piled up outside the corral every day for a two- to three-month period, until enough material has accumulated to be applied to a certain area. For three days feces were collected directly from the

rectum of three cows selected at random in the morning and afternoon (18 cows). Three more samples day⁻¹ of freshly deposited manure were collected from the farmyard during the same day for a total of nine samples. The total manure collected during the three days of collection was mixed, simulating the system practiced by the farm owner. Randomized samples were taken from the manure at 15, 30 and 45 days and analyzed to determine nitrogen and dry matter content.

2.2.5 Plant structural and morphological variables

During each sampling period, each plant (1 m²) was further sub-sampled to determine seven plant characteristics: plant height, number of stem, biomass, dry matter proportion, number of leaves stem⁻¹, leaf length and the leaf–stem ratio. Plant height was measured with a ruler from the base of the plant to the apex or fold of leaves located on the highest stem; ten measurements were taken per plant for each sampling time and the average was determined. The number of stems per plant was count, including all tiller sizes. Green biomass plant⁻¹ was assessed at a 5 cm cut height. Concurrently, a sub-sample was selected to determine dry matter content. The samples were oven dried at 60°C for 96 hours to constant weight of the stems. The differences between green and dry matter weight were used to determine dry matter percentage. A sub-sample of five stems per plant was also selected to assess the average number of leaves per stem. The same five stems were also used to measure leaf length. The leaf–stem ratio was calculated by dividing the number of leaves by the number of stems for the sub-sampled stems. In the results and discussion section the leaf–stem ratio is discussed separately as the proportion of biomass allocated to leaves and stems. Limitations in the budget and the analysis cost forced to determine nitrogen concentration of the whole plant for the initial and final sampling date only, but it was assessed for all treatments and cutting intervals.

2.2.6 Statistical Analysis

The statistical analysis consisted mainly of a Repeated Measurement Analysis, considering the effects of treatments and the repeated cutting intervals applied during the experiment. The standard errors of the means were used to detect differences

between treatments. Given the lack of a repeated sampling effect, an Analysis of Variance was used for additional analyses, such as assessing changes in nitrogen and organic matter content in the soil and manure (GENSTAD, 6.1).

2.2.7 Nitrogen balance, use and recovery efficiency

The nitrogen balance was estimated relating the quantities of nitrogen applied to the soil through the manure to the nitrogen extracted by the plant. The initial determination of nitrogen concentration in the applied manure, and the analysis of nitrogen contained in the whole plant were used to determine the cumulative nitrogen balance. Nitrogen use efficiency (NUE) (kg DM kg⁻¹ N) and nitrogen recovery efficiency (NRE) (%) were determined using the equations proposed by Novoa and Loomis (1981) [Equation 1 and 2]. Nitrogen residual in manure was determined collecting all the residual manure per assessed plant and analysing nitrogen concentration.

$$NUE = \frac{F_{DM} - C_{DM}}{N_a} \quad \text{[Equation 1]}$$

where:

F_{DM} = Fertilized dry matter yield (kg)

C_{DM} = Control dry matter yield (kg)

N_a = Nitrogen applied (kg)

$$NRE = \frac{100(F_N - C_N)}{N_a} \quad \text{[Equation 2]}$$

where:

F_N = Fertilized nitrogen yield (kg)

C_N = Control nitrogen yield (kg)

N_a = Nitrogen applied (kg)

2.3 Results and discussion

2.3.1 Nitrogen and organic matter content in the soil

The soil chemical analysis for nitrogen and organic matter concentration at the end of the experiment did not detect any statistically significant differences ($p > 0.05$)

between treatments. The three fertilized treatments showed slightly higher values than the control treatment. So, the mean values of nitrogen (0.21%) and organic matter (3.01%) in the three fertilized treatments were higher than the initial values.

2.3.2 Nitrogen and organic matter content in applied manure

At the end of the experiment, the changes in organic matter content of the applied manure i.e. the disappearance rate, showed statistically significant differences between treatments for the cutting intervals of 30 and 45-days, while for the cutting interval of 60-days there were not differences between treatment. (Table 2.1). Is observed an influence by the cutting interval, as short as was it, the difference among treatments was clearer. However, analysing treatments and cutting intervals together, the values for turnover rate are not consistent and it could be explained by the used methods to apply the manure (over the plant) and the role of the macro-organism that mediates in the manure decomposition, i.e. earthworms, black beetles, which process the manure without an order of position.

Table 2.1. Mean turnover rate (%) of organic matter in the applied manure for the experimental period (180 days).

Treatment Rate (tonnes/ha)	15 t	30 t	60 t
Cutting Interval			
30 days	55.62c	72.59b	84.65a
45 days	65.32b	74.23a	73.05a
60 days	70.72a	68.64a	71.23a

Means with different letters in the same row are statistically different (p<0.05)

Overall, the average organic matter content in the applied manure had a daily disappearance rate of 0.184% (Figure 2.3). The average nitrogen content varied little over the sampling period (0.27% ±0.072) Figure 2.3).

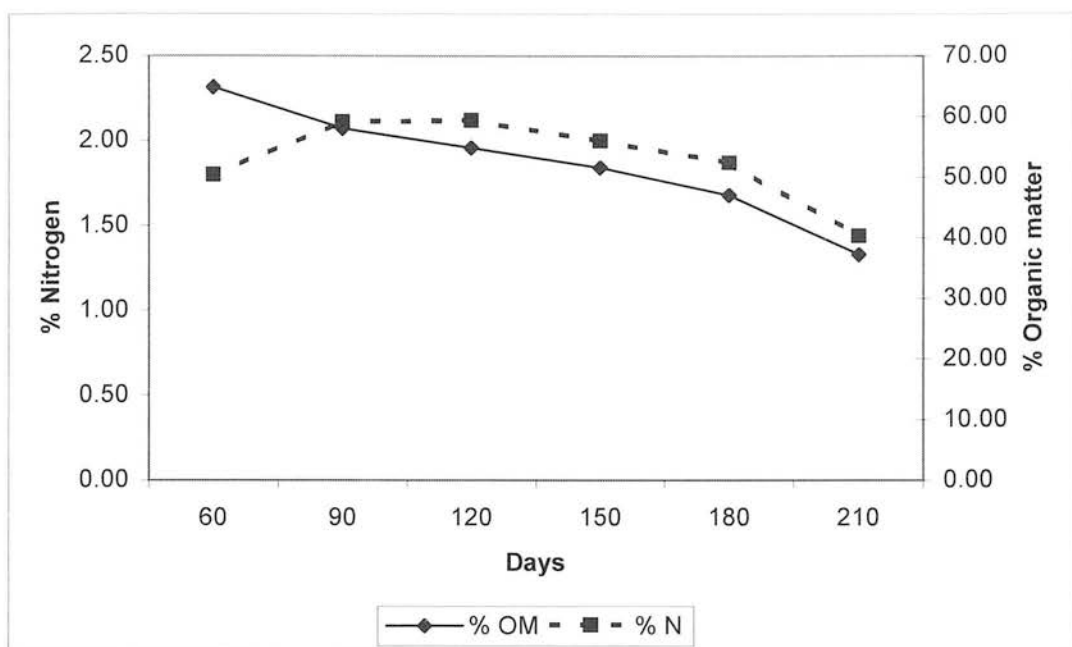


Figure 2.3. Nitrogen and organic matter concentration (%) in the applied manure during the experimental period (180 days)

2.3.3 Nitrogen and organic matter content in stored manure

For the manure taken directly from the cows rectums and then stored for 45 days, the total nitrogen concentration showed no statistical differences ($p>0.05$) for that period. The mean values were 1.81% N for manure collected directly from the cows, 1.86% from the farmyard and 1.85% after 45 days of storage. During the process, the manure decreased by 6.56% in organic matter and 3.7% in humidity.

2.3.4 Biomass production and nitrogen concentration

Biomass production was larger in the treatment with the highest manure application (Table 2.2). The response of Napier grass to manure fertilization was always positive: the higher manure doses always resulted in higher biomass production due to the cumulative effect of the nutrients applied in the individual manure doses. The statistical analysis showed significant differences between some, but not all treatments for each cutting interval ($p<0.01$; Table 2.2). Variation indicates a grass growth dynamic dependence to cutting interval and the nutrients availability. However, the analysis of biomass production per extra ton of manure added showed that the effect was greater for the cutting interval applied than for the

quantity of manure added. So, the Napier grass biomass production as effect of manure fertilization showed better performance with 60 days cutting interval.

Table 2.2. Average biomass production (Kg DM ha⁻¹) per treatment and per cutting interval.

Cut Int./Treat	0 t	15 t	30 t	60 t
30 days	1928 b	2146b	2223b	3996a
45 days	3867c	4800b	5505b	6706a
60 days	5869d	7634c	9906b	13503a

Means with different letters in the same row are statistically different (p<0.05)

Nitrogen contained in the whole plant had a positive response to manure fertilization, since there were significant differences (p<0.01) between the control and the treatments with fertilization (Table 2.3). For each cutting interval, the nitrogen concentration in the control was always approximately 10% less than the nitrogen concentration of any of the plants that had received manure. For all treatments, except one, the nitrogen concentration in the whole plant decreased with an increase in the cutting interval.

Table 2.3. Nitrogen concentration (%) in the whole plant per treatment and cutting interval.

Cut Int./Treat	0 t	15 t	30 t	60 t
30-days	1.5c	1.76b	1.73b	1.86a
45-days	1.13c	1.29b	1.49a	1.50a
60-days	1.06c	1.31a	1.16b	1.22b

Means with different letters in the same row are statistically different (p<0.01)

2.3.5 Plant structural and morphological variables

The plant dry matter proportion did not show any statistical differences (p>0.05) between treatments. However, as the cutting interval increased, the dry matter proportion increased. This response is due to changes in the plant growth stage, whereby as the plant ages, the fiber content increases and consequently the proportion of dry matter. There were also significant (p<0.001) differences in the

proportion of stems plant⁻¹ between the different manure treatments, with the highest manure application resulting in the highest stem proportion for each cutting interval, except for the 45-days cutting interval with 30 and 60 t of manure (Table 2.4).

Table 2.4. Means of leaf – stem ratio for each manure application treatment and cutting interval.

Treatment Rate (tonnes/ha)	0 t	15 t	30 t	60 t
Cutting Interval	Stem proportion (%)			
30-days	33.73b	33.36b	33.07b	39.59a
45-days	38.39b	39.89ab	42.55a	42.47ab
60-days	53.14b	51.80b	54.60b	58.78a
Cutting Interval	Leaf proportion (%)			
30-days	66.27a	66.64a	66.93a	60.41b
45-days	61.61a	60.11a	57.45b	57.53ab
60-days	46.86a	48.20a	45.40a	41.22b

Means with different letters in the same row are statistically different (p<0.01)

The leaf proportion showed an inverse relation with the stem proportion, considering that both variables should sum to 100%. The higher the amount of fertilizer applied, the higher the proportion of stems (Table 2.4). Independent of the treatment, plant age caused an increase in the proportion of stems. In addition, the longer cutting interval also increased the proportion allocated to the stems versus the leaves.

The evaluation of plant height throughout the experiment allowed for the detection of a clear effect of manure fertilization on the growth of the pasture. For all cutting intervals, the highest manure treatment resulted in the tallest plants (Table 2.5).

The number of stems per plant did not show a response to manure fertilization (Table 2.5). Therefore, the stem population indicates that the number of stems per plant or area is not dependent of the nitrogen available in the soil, meaning that the weight biomass difference per treatment is the result of the individual stem growth.

However, there was difference in number of stem per plant between cutting interval hence the number of stems was higher when the cutting interval was shorter.

Table 2.5. The impact of manure fertilization and cutting interval on plant height (m), number of stems plant⁻¹, leaf number stem⁻¹, and leaf length (cm).

Treatment Rate (tonnes/ha)	0 t	15 t	30 t	60 t
Cutting Interval	Plant height (m)			
30-days	0.66c	0.74b	0.74b	0.83a
45-days	0.99c	1.06b	1.10b	1.20a
60-days	1.29c	1.40b	1.39b	1.63a
Cutting Interval	Stem number plant ⁻¹			
30-days	127.67b	126.69b	135.42ab	144.67a
45-days	112.92a	104.16a	71.17c	90.04b
60-days	61.56a	68.11a	73.89a	74.11a
Cutting Interval	Leaf number stem ⁻¹			
30-days	6.18c	6.41b	6.02c	6.88a
45-days	7.52bc	7.7ab	7.45c	7.78a
60-days	9.04b	8.68c	9.61a	9.72a
Cutting Interval	Leaf length			
30-days	43.01c	47.11b	48.04b	49.58a
45-days	55.33c	59.84b	59.45b	67.44a
60-days	67.00d	69.00c	71.93b	75.77a

Means with different letters in the same row are statistically different (p<0.05)

The number of leaves per stem was affected by the manure treatment and for the majority of the treatments showed statistical differences (p<0.05) (Table 2.5). However, the relation of number of leaves per stem and plant height was not consistent.

There was also a statistical significant difference for leaf length (Table 2.5), so, the nitrogen fertilizer through the manure application has influence in the individual leaf growth. However, this difference is inadequate to influence the leaf-stem ratio, which always was higher for the highest manure treatments.

2.3.6 Cumulative nitrogen applied, nitrogen extracted, nitrogen balance, nitrogen use efficiency, recovery efficiency, and nitrogen residual in manure

The cumulative nitrogen applied shows a high quantity of nitrogen concentrate in the manure fertilizer (Table 2.6); however, is important to clarify that only a part of these quantities of nitrogen are in an available condition and the majority proportion will depend of the decomposition organic matter rate.

Cumulative nitrogen extracted for each treatment was dependent of nitrogen concentration in the harvest biomass. Nitrogen uptake by the plant indicates a dependence on the cutting interval, a factor that defines the age stage for the plant, i.e. for 30-days of cutting interval the mean of biomass was around 75% less than the biomass for 60-days of cutting interval; however, the difference in nitrogen uptake oscillated from 10 to 35%.

The nitrogen balance at 180 days showed that for the treatment of 15 t ha⁻¹, the nitrogen balance had a deficit of 125 kg of N ha⁻¹ (Table 2.6) The equilibrium between nitrogen applied and nitrogen extracted was obtained with a cutting interval of 60-days for the treatment of 30 t ha⁻¹ (Table 2.6). The 60 t ha⁻¹ of manure treatment showed a positive nitrogen balance for all cutting interval (Table 2.6). The amount of nitrogen extracted as well as the nitrogen balance clearly explain why Napier grass declines in productivity and soil fertility decreases during a relatively short time when farmers do not manage the crop with a specific fertilizer plan.

The nitrogen concentration of the residual manure indicated that the nitrogen extracted by the plant not only came from the nitrogen provided with manure but also from the initial nitrogen in the soil. However, the residual manure can be considered as material that will decompose and will thus return the transformed nitrogen to the soil. Another important factor to consider for this residual manure is its organic matter proportion, which improve the moisture retention.

Table 2.6. Relationship between cumulative nitrogen applied, cumulative nitrogen extracted, cumulative nitrogen balance, nitrogen use efficiency, nitrogen recovery efficiency, and nitrogen in residual manure.

Treatment Rate (tonnes/ha)	0 t	15 t	30 t	60 t
Cutting Interval	Cumulative nitrogen applied (kg)			
30-days	0	175	350	699
45-days	0	175	350	699
60-days	0	175	350	699
Cutting Interval	Cumulative nitrogen extracted (kg nitrogen in dry matter)			
30-days	183	225	231	446
45-days	175	248	328	402
60-days	187	300	345	494
Cutting Interval	Cumulative nitrogen balance (kg nitrogen ha ⁻¹)			
30-days	-183	-50	119	254
45-days	-175	-73	22	297
60-days	-187	-125	5	205
Cutting Interval	Nitrogen use efficiency (kg DM kg ⁻¹ nitrogen applied)			
30-days	-	7.5	5.1	17.7
45-days	-	21.3	18.7	16.2
60-days	-	30.3	34.6	32.7
Cutting Interval	Nitrogen recovery efficiency (%)			
30-days	0	24	14	38
45-days	0	42	44	32
60-days	0	65	45	44
Cutting Interval	Nitrogen in residual manure (kg nitrogen ha ⁻¹)			
30-days	-	57	75	73
45-days	-	37	68	195
60-days	-	29	115	200

2.4 Discussion

The feed quality of cows and the process of collecting, storing, and handling manure before its utilization have a strong impact on the final nitrogen concentration

of manure (Smith & Chambers, 1993; Lupwayi *et al.*, 2000; Sommer & Hutchings, 2001; Kekasi *et al.* 2003). The manure used in the current study had a high nitrogen concentration (1.8%) in relation to other studies. This was a result of the high proportion of concentrates (35%) and high forage quality fed to the cattle, and the additional influence of good management of the manure, which was collected and stored every day until its application. The only slight variation in nitrogen and organic matter concentration of the soil among treatments is an indication that throughout the 180 days of the study, the pattern of manure application had little impact on the soil characteristics. However, it is possible that the sampling depth of 20 cm was too deep to detect changes in soil quality, considering that during the collection process of the residual manure a high number of superficial thin roots was observed, which could have been produced by the plant under the stimulation of the manure that was applied on top of the soil. Therefore, it is possible that the plant absorbed the nitrogen that was supplied in the applied manure through these superficial roots located in the superficial layer (up to 5 cm in depth). Nitrogen volatilisation was not determined in this study and could have been another factor that could have contributed to the potential loss of nitrogen.

The turnover rate of organic matter contained in the applied manure may be determined by the cutting frequency. The results showed a significant variation in the turnover rate of organic matter in manure among the treatments for the cutting interval of 30 days. As the manure dose increases, the turnover rate increases, but this effect can not be clearly explained, because for the other two cutting intervals, e.g., 45 and 60 days, the turnover rate of organic matter in the manure did not show a strong variation between treatments and cutting interval. This demonstrated that the turnover rate did not depend on the soil–manure area relationship when the manure was not frequently disturbed by the harvest of the plants. Therefore, the treatment effect had less of an impact as the cutting interval increased.

The method of manure application was aboveground, which is a common practice for smallholder and medium-size farmers and is mainly due to the labour requirements. This practice also protects the soil, because the incorporation of organic matter through conventional tillage is damaging to the soil. It disrupts the structure of the soil and the degradation of soil organic matter (Elliott, 1986; Kay,

1990; Beare *et al.*, 1994). A no-tillage treatment leaves the soil undisturbed and promotes the accumulation of organic matter on the soil surface as mulch (Beare *et al.*, 1994; Paré *et al.*, 1999). It also improves soil aggregation, although this process takes some time (Havlin, 1990; Aoyama *et al.*, 2000). This might partially explain why the effect of the manure application on organic matter accumulation was not found at a soil depth of 20 cm.

The almost constant concentration of nitrogen in the applied manure throughout the study showed that a negligible amount of nitrogen was lost during the manure storage. However, the substantial decreases that were observed in the proportion of organic matter indicate that under the local weather conditions, the organic matter of the applied manure should disappear completely through degradation in 543 days. Beside, it is generally agreed (Bloodgood and Robson, 1969) that the local weather conditions and the storage method impact the rate of nitrogen loss during decomposition. Lekasi *et al.* (2001) found a range between 2.0% and 30.1% of nitrogen losses during the composting phase, with significantly higher losses in manures from low-concentrate diets than from high-concentrate diets. In the present study the samples were not mixed with urine, which can also reduce the initial ammonia concentration in the manure. Beauchamp (1986) stated that rainfall dilutes the total ammonia in manure, and thus reduces the ammonia emission rate after application. However, during the monitoring and sampling process we found that manure exposed to the natural environment quickly formed a crust, which could have protected it from the effects of sun and rainfall.

The final soil analysis and the positive response of Napier grass to the manure application indicated that manure fertilization had a positive impact on crop performance. In general for manure, the complete ammonium-nitrogen ($\text{NH}_4\text{-N}$) compound and part of the nitrates are available for the crop (Beauchamp, 1983). Approximately 33% to 45% of the initial nitrogen concentration of fresh manure is $\text{NH}_4\text{-N}$ (Smith and Chambers, 1993). These findings would explain the immediate response of the pasture to manure fertilization in this study: for all manure treatments the first cut had the highest yield.

To achieve an annual equilibrium of nitrogen, the amount of manure required to compensate for the extracted nitrogen should be around 30 t of dry matter per hectare. It is important to note that the experiment was conducted during the rainy season, e.g., summer and autumn, which is the period of highest biomass production. It might, therefore, be probable that the remaining nitrogen in the residual manure at the end of the experimental period would be adequate to cover the requirements for two additional cuts or harvests when Napier grass biomass production is lower before a new application of manure is made. The nitrogen use efficiency analysis demonstrated that a cutting interval of 60 days was the most advisable for Napier grass. In terms of the plant's physiology, this cutting frequency permitted the plant to benefit more efficiently from the environmental conditions. This outcome is similar to the results of Alves dos Santos *et al.* (2001) who assessed Napier grass during the rainy and dry season and determined that the best cutting interval was 60 days for the rainy season and 90 days for the dry season.

The treatment with the lowest manure dose and cutting interval of 60 days had the highest nitrogen recovery efficiency (Table 6). However, the most relevant characteristic of the nitrogen recovery efficiency in this study was that it was more a function of the cutting frequency than the manure application treatment. Therefore, the cutting frequency of 60 days was the most efficient and showed light differences among treatments.

For each manure dose increase per treatment, the biomass production also increased. This demonstrated that Napier grass is a species with a high potential for producing forage. For cut and carry systems during the rainy season, a cutting interval of 60-days is the most advisable, since, independent of the manure treatments, the results showed little variation in the relationship between total dry matter produced per kg of nitrogen applied. We found 19.6 kg biomass m⁻² kg⁻¹ N for the 15 t manure treatment, 22.4 kg biomass m⁻² kg⁻¹ N for the 30 t manure treatment, and 21.2 kg biomass m⁻² kg⁻¹ N for 60 t of manure ha⁻¹ treatment. These results are similar as the results of Mwangi (1999), although he only evaluated the first cut. These results are also similar to several other studies where a cutting frequency of 50 to 70 days was applied and, in general, the 60-days cutting interval was considered to

be the optimum (Machado *et al.*, 1996; Muia *et al.*, 1999; Alves dos Santos *et al.*, 2001; Deschamps and Brito, 2001; Ferrari and Lavezzo, 2001).

In the current study the nitrogen concentration of the whole plant decreased when the cutting interval increased, so at 60-days the protein concentration was the smallest, and less than the nitrogen concentration at a cut interval of 45 and 30-days. However, this decrease was more than compensated for by the higher biomass production, because the nitrogen uptake by the plant was 48% and 75% higher for 45 and 60-days cutting interval when compared to the 30-days cutting interval.

Plant height was the most sensitive variable to any change in environmental conditions. The tallest plants were observed during the first sampling of the 60-days cutting frequency. As the season advanced from summer to autumn, the mean plant height decreased from 1.99 to 1.55 m. This was similar to the plant height measured by Deschamps and Brito (2001) for three different varieties of Napier grass in a study conducted using inorganic fertilizer.

For the leaf – stem ratio, the non-fertilizer and the treatment with the smallest amount of manure application had a higher leaf fraction in relation to the other two fertilizer treatments. However, in this case, the fraction of leaves was not a useful indicator for plant production, as the treatments with the higher amounts of manure application produced higher biomass levels, which over-compensated for the lower fraction of leaves. The fraction of stems was inversely proportional to the fraction of leaves.

2.5 Conclusions

It can be concluded that under the initial soil conditions of the experiment, biomass production showed an immediate response to the application of manure and this effect was maintained during the entire experimental period of 180 days. The results showed that it is viable to use Napier grass as a component of high forage production, but it is necessary to apply a plan of manure recycling to maintain the soil fertility and biomass production.

The dose of 30 t DM manure ha⁻¹ is the most recommendable for farmers, considering the grass response and the limitation to be available this material.

Abstract

Napier grass is a forage resource that has been widely distributed during the last few years in dairy production systems. Its high biomass production and nutrient requirements, however, have implications to better define its agronomic characterization based on local soil conditions, climate characteristics and crop management. The goal of this study was to evaluate the interaction of nitrogen fertilizer and temperature variation due to seasonal changes. The experimental period included both the rainy and dry seasons, with irrigation complementing the dry season. Two nitrogen fertilizer levels and a control were applied (0, 250 and 500 kg N ha⁻¹ year⁻¹) and two cutting intervals, i.e., 30 and 60-days, were defined for evaluation of the pasture. The weather variables such as precipitation and daily temperature (maximum and minimum) were recorded. The difference in mean temperature between the five hotter months in relation to the two colder months (June and July) was 5.0°C. Both temperature and nitrogen fertilizer significantly affected growth of all the variables that were measured, including plant height, stem number per plant, leaf length, leaf number per stem, biomass per plant, dry matter proportion per plant and leaf – stem ratio. Biomass production increased by 290.4 kg DM ha⁻¹cut⁻¹ for each degree Celsius increase in temperature. The nitrogen concentration of the whole plant only had a statistical difference ($p < 0.05$) among treatments for the 60-days cutting interval. The Napier grass response to nitrogen fertilization over 30-days cutting interval, but it is affected by the temperature decrease during the two colder months, which effect is necessary to consider in the pasture performance.

3.1 Introduction

The milking basin of Santa Cruz, Bolivia consists of more than six thousand farmers whose daily milk production exceeds 450,000 l. For the majority of farmers, more than 85% of their income depends on livestock production (Bernues *et al.*, 1998). The climate of this basin is tropical with two distinct seasons, which affect forage production: a hot rainy summer from October to March and a dry winter from April to September. During the last five years the drop in local milk prices caused by international markets has forced the Santa Cruz' basin farmers to be more efficient in their dairy production. In particular it has become necessary to improve the quality and quantity of pastures for dairy cattle, as forage is the cheapest food resource for livestock. This has to be complemented with efficient land use as a result of limited land availability (Anindo & Potter, 1986; Kubota *et al.*, 1994; Muia *et al.*, 1999). In sub-humid areas Napier grass stays green during the dry season, which characteristic is appreciated by farmers (Boonman, 1997).

In the study area the regional improvement of rural electrification together with its geologic characteristics provide for suitable conditions to apply supplemental water through irrigation in order to produce green forage during the dry season. However, to successfully develop irrigation as a component of the farming systems, one first has to determine the effect of seasonal changes in temperature on the performance of pastures. Thus, the potential of Napier grass for forage production can be evaluated to assess the efficacy of initiating an irrigation program.

According to Jones (1985), temperature is one of the most important parameters that affect the growth of C₄ grasses, as impacts photosynthesis as well as dry matter accumulation and expansion growth and other aspects of crop growth and development. An accurate identification of the plant-temperature response is thus a prerequisite to successful crop systems modelling and the application of such models to systems management (Weika and Hunt, 1999).

The goal of this study, therefore, was to assess the effect of temperature fluctuations on the growth dynamics and sward structure of Napier grass, and the

response of Napier grass to nitrogen fertilizer applications under different cutting intervals.

3.2 Material and methods

The experiment was conducted at the Estación Experimental Agrícola of Saavedra (EEAS), Santa Cruz, Bolivia (lat. 17° 14' S; long. 63° 10' W; alt. 320 m.a.s.l). Weather data were recorded by a meteorological station located 1km from the experimental site. Mean monthly temperatures for the last 47 years showed that the coolest months were June and July, with an average daily temperature of 20.2°C, and the hottest months were December and January, with an average daily temperature of 25.8°C. The wettest month was January, with a total rainfall of 224 mm, and the driest month was July, with a total rainfall of only 42 mm (Busqué and Herrero, 2000). Within the experimental period, the mean temperature variation between the hottest (October) and coldest month (June) was 8.8°C, while the mean temperature variation between the five hottest months and the three coldest months was 5.0°C (Figure 3.1).

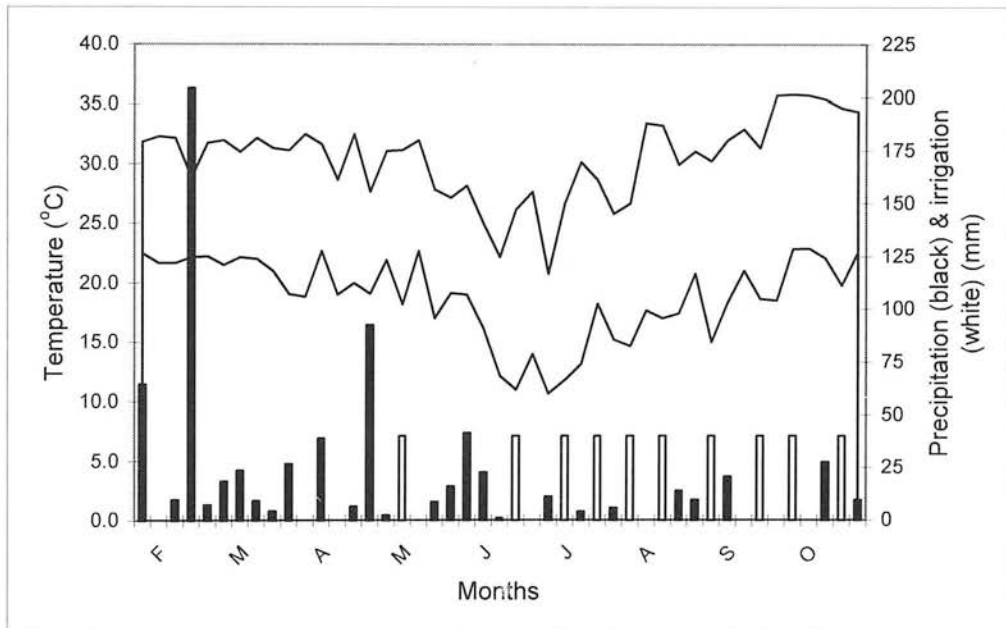


Figure 3.1 Minimum and maximum mean daily temperature (lines and left vertical axis), precipitation (black columns and right vertical axis) and irrigation (white columns and right vertical axis) for the experimental site from February to October 2002.

3.2.1 Soil characterization

The initial soil sampling at the experimental site was a depth of 20 cm. The texture was loamy clay, comprising 21% sand, 24% clay and 55% lime, respectively. The soil had a pH of 6.3 and a bulk density of 1.58 g/cm³. An initial chemical analysis showed a mean nitrogen concentration of 0.155% (± 0.032).

3.2.2 Experimental area and design

The total plot area was 384 m², which was divided into 18 plots of 16 m² (4 x 4 m). The experimental design was a randomized split plot complete block design. Plant density was 1 plant per m², resulting in 16 plants in each plot and a total of 384 plants. The experiment comprised three different nitrogen fertilizer treatments, including 0 kg, 250 kg and 500 kg nitrogen ha⁻¹ year⁻¹, with three replicates and two cutting intervals, i.e., 30 and 60-days. The dose of nitrogen that was applied at the 30-days cutting interval was 20.75 and 41.5 kg ha⁻¹ cut⁻¹, and at 60-days cutting interval was 41.5 kg ha⁻¹ cut⁻¹ and 83 kg ha⁻¹ cut⁻¹ for the two nitrogen fertilizer treatments (250 and 500 kg N ha⁻¹ year⁻¹, respectively). The trial started on February 25th and ended on October 29th of 2002 for a total of 240 days.

3.2.3 Pasture and management

The initial crop was planted on December 7th 2001. Mature plants of Napier grass were used to establish the experimental area: two mature stems with three nodes each were planted to form a plant. After 82 days of growth the grass was cut down to 0.5 cm above the soil surface, thus providing the initial conditions for the experiment. Nitrogen was then applied every 30 and 60-days for the 30 and 60-days cutting intervals, respectively. The nitrogen dose was adjusted according to the treatment and cutting intervals. For instance, for the 500 kg treatment and the 30-day cutting interval, the total dose was divided by 12 applications and by 6 applications for the 60-days cutting interval. During the dry season the plots were irrigated every 14 days through a gravity system that delivered approximately 46 mm of water per application (Figure 3.1).

3.2.4 Measuring plant variables

Seventy-two plants (1 plant per m^2) were randomly selected for monitoring. Samples were taken at every cutting interval, thus either 8 for the 30-days cutting interval or 4 for the 60-days cutting interval, making a total of 432 samples. Cutting periods were numbered one to eight. During each sampling period, each plant was further sub-sampled to determine eight variables: plant height, stem number plant^{-1} , biomass plant^{-1} , leaf length, leaf number stem^{-1} , leaf-stem rate, and dry matter-rate. In addition, elongation (cm day^{-1}), leaf appearance rate and daily growth rate (kg DM day^{-1}) were calculated. Plant height was measured with a ruler, with ten measurements per plant for each sampling time. Height measurements were taken from the base of the plant to the apex or fold of leaves located on the highest stem.



Figure 3.2. Experimental area of Napier grass under nitrogen fertilizer treatments and different cutting intervals

The stem number per plant was simply counted, including all tiller sizes. Green biomass plant^{-1} was assessed at the experimental area at a 5-cm cut height. Concurrently, a sub-sample per plant was selected to determine dry matter content. The samples were dried in an oven at 60°C for 96 hours until constant moisture of

the stems. Differences between green and dry matter weight were used to determine dry matter percentage. A sub-sample of five stems per plant was also taken to assess the average leaf number stem⁻¹. Those five stems were also used to measure leaf length. The leaf–stem ratio was calculated by dividing leaf number by stem number (in this case 5) on the sub-sampled stems. The nitrogen concentration of the whole plant was assessed for all treatments and cutting intervals for the initial and final sampling dates (Method 984.13, AOAC, 1995).

The statistical analysis consisted mainly of a Repeated Measurement Analysis, considering the effects of treatments and the repeated cutting intervals applied to the monitored plants during the experiment. Standard errors of the means were used to detect differences between treatments. To determine the temperature effect on plant performance, a Covariance analysis was applied using daily mean temperature as co-variable. This Covariance analysis was conducted independently of the treatments. Given the lack of a repeated sampling effect, an Analysis of Variance was used for additional analyses such as assessing changes in nitrogen and organic matter content in the soil and manure.

3.2.5 Measuring gross nitrogen dynamic

Nitrogen use efficiency (NUE) (kg DM kg⁻¹ N) and nitrogen recovery efficiency (NRE) (%) were determined using the equations proposed by Novoa and Loomis (1981):

$$NUE = \frac{F_{DM} - C_{DM}}{N_a} \quad \text{[Equation 1]}$$

where:

F_{DM} = Fertilized dry matter yield (kg)

C_{DM} = Control dry matter yield (kg)

N_a = Nitrogen applied (kg)

$$NRE = \frac{100(F_N - C_N)}{N_a} \quad \text{[Equation 2]}$$

where:

F_N = Fertilized nitrogen yield (kg)

C_N = Control nitrogen yield (kg)

N_a = Nitrogen applied (kg)

Nitrogen loss through leaching was determined using the equation proposed by Willigen (2000), which calculate leaching for a year, including total annual precipitation, so, for this experiment the values for precipitation, nitrogen fertilization, and the grass's nitrogen uptake were adjusted at the time duration of the experimental period.

$$N - leaching = ((0.0463 + 0.0037)(\frac{P}{CL}))(F + D)(NOM - U) \text{ [Equation 3]}$$

where:

P = precipitation (mm year⁻¹)

CL = clay (%)

L = layer thickness (m) = rooting depth, derived from Allen *et al.* (1998)

F = nitrogen fertilization (kg ha⁻¹ year⁻¹)

D = decomposition rate (year⁻¹); assumed to be 0.016

NOM = amount of nitrogen in soil organic matter (kg ha⁻¹)

U = nitrogen uptake by crop (kg ha⁻¹ year⁻¹)

Gaseous nitrogen emission from denitrification and volatilization was calculated using:

$$GNL = (0.025 + P(8.55 * 10^{-4})) + F(1.725 * 10^{-2}) + 0.117C + 0.113F \text{ [Equation 4]}$$

(IFA/FAO, 2001)

where:

GNL = gaseous nitrogen losses (kg N ha⁻¹)

P = annual precipitation (mm)

F = fertilizer input (kg ha⁻¹)

C = organic carbon content (%)

GNL was calculated considering treatment effect only, because the equation does not allow for determining the impact of cutting interval.

The gross N balance was calculated using the main external sources of nitrogen (deposition and fertilization), and the factors of nitrogen loss (leaching and emission). A value for deposition of $5 \text{ kg ha}^{-1} \text{ year}^{-1}$ was used, based on results obtained by Brye *et al.* (2003).

3.3 Results and discussion

3.3.1 Measured plant variables

Growth rate was highest in the 60-days cutting interval, independent of the treatment, whilst the cutting interval of 30-days was not sufficient for the plant to respond to the nitrogen application (Table 1).

Table 3.1. Means of growth rate (GR) and biomass production (BP) of Napier grass under various nitrogen fertilizer application rates and cutting intervals (SE: GR=6.65; BP=380).

Cut Int./Treatment Rate ($\text{kg ha}^{-1} \text{y}^{-1}$)	0 kg N	250 kg N	500 kg N
	Growth Rate ($\text{kg DM ha}^{-1} \text{d}^{-1}$)		
30-days	59.76 a	58.27 a	61.55 a
60-days	72.19 c	83.62 b	95.27a
	Biomass production ($\text{Kg DM cut}^{-1} \text{ha}^{-1}$)		
30-days	1861a	1825a	1911a
60-days	4431c	5151b	5891a

Means with different letters in the same row are statistically different ($p < 0.05$)

Biomass production increased by $290.4 \text{ kg DM ha}^{-1} \text{cut}^{-1}$ for each degree Celsius increase in temperature. The fertilizer treatments had significant differences ($p < 0.05$) in the 60-days cutting interval only. However, this positive effect on pasture performance was proportional at the nitrogen dose application. So, the mean pasture

response for 250 and 500 kg N ha⁻¹year⁻¹ was similar, 17.4 and 17.6 kg DM increase kg⁻¹ of nitrogen applied, respectively.

In the structural distribution, the dry matter (DM) proportion of Napier grass was influenced by the seasonal variation in temperature. The analysis showed that DM increased 0.18% per each Celsius degree over the monthly mean minimum temperature, independently of the treatments and cut frequency. The nitrogen fertilizer application did not have an impact on the DM rate of Napier grass, so, there were differences between cutting intervals but not between treatments.

For the leaf–stem ratio (Table 2), both components of the plant showed a relation that was inversely proportional in response to the variation in temperature. Therefore, when the stem percentage increased due to the hot season, the proportion of leaves decreased. This change amounted to 0.57% per °C increase. The treatments with N fertilizer were significantly different ($p<0.01$) for the leaf–stem ratio, showing that the adding N increased the proportion of stems, and the faster development of the stems during the hot season had a direct impact on the increase in the DM proportion.

Table 3.2. Proportion of leaves and stems of Napier grass as affected by nitrogen fertilizer application and two cut interval (SE = 1.8)

Cut Int./Treat	0 kg N	250 kg N	500 kg N
Leaves (%)			
30-days	77.52a	75.89a	68.78b
60-days	57.91a	54.15b	53.79b
Stems (%)			
30-days	22.48b	24.11b	31.22a
60-days	42.09b	45.85a	46.21a

Means with different letters in the same row are statistically different ($p<0.01$)

The stem population showed a strong response to the cold season (Table 3.3), independent of the different treatments. The statistical analysis showed that the stem population decreased 6.73 stems per plant for each °C increase. Besides, there was no

effect of nitrogen fertilizer treatments and the two cut frequencies. However, the 30-day cut interval had a higher stem population than the 60-days cut interval ($p<0.01$).

Table 3.3. Means of stem per plant (SP), plant height (PH), elongation (E), leaf appearance rate (LA) and leaf length (LL) of Napier grass under three N fertilizer application rates and two cut intervals (SE: SP=5.58; PH=0.048; E=0.16; LA=0.075; LL=2.27).

Cut Int. / Treatment	0 kg N	250 kg N	500 kg N
	Stems plant ⁻¹		
30-days	80.28b	83.50ab	88.46a
60-days	40.55ab	38.06b	43.45a
	Plant height (m)		
30-days	0.80c	0.86b	0.94a
60-days	1.56b	1.71a	1.73a
	Plant elongation (cm d ⁻¹)		
30-days	2.60c	2.79b	3.07a
60-days	2.54b	2.78a	2.81a
	Leaf appearance rate (day leaf ⁻¹)		
30-days	4.40a	4.10b	3.69c
60-days	6.21a	5.11b	4.90c
	Leaf length (cm)		
30-days	51.27a	49.46a	53.65a
60-days	78.89b	80.03b	87.07a

Means with different letters in the same row are statistically different ($p<0.01$)

Plant height responded to the temperature changes between the hot and cold seasons, and the pasture increased its height 0.076 m per °C increase in temperature. Moreover, plant height also responded to N fertilization, and showed significant differences ($p<0.01$) among treatments in the two cut frequencies. The plant elongation (cm day⁻¹) variable was affected by the temperature fluctuation throughout the experiment. This effect caused an increase of 0.164 cm per day per °C increase over the monthly mean temperature registered during the cold season. The

elongation variable also responded to N fertilization, and it showed differences ($p<0.01$) between treatments as well as between cut intervals (Table 3.3).

Independent of the treatments, the leaf appearance rate (days leaf^{-1}) decreased 0.204 days in the appearance of one complete leaf per $^{\circ}\text{C}$ increase. This means that during the process of the appearance of one complete leaf, the variation of 5°C will be equivalent to reduce the total time required for leaf appearance by one day. According the analysis of the treatments effect, the leaf appearance rate response to N fertilization found significant differences ($p<0.01$) among treatments and cut intervals (Table 3.3).

The response of leaf length to the change in seasonal temperature was 3.66 cm per $^{\circ}\text{C}$ increase. Thus, this complements the results obtained in other variables related to forage yield, such as biomass and growth rate. The effect of treatment was present in the two cut intervals, being more evident in the treatment with the highest N application (Table 3.3).

The chemical analysis for nitrogen concentration of the whole plant showed statistical differences ($p<0.05$) for the highest dose of nitrogen in the 30-days cutting interval and among the three treatments ($p<0.01$) in the cut interval of 60-days (Table 3.4).

Table 3.4. Means of N concentration of the whole plant of Napier grass under nitrogen fertilization and two cut intervals (SE = 0.12).

Cut Int. / Treatment	0 kg N	250 kg N	500 kg N
30-days	1.92b	1.91b	2.05a
60-days	1.22c	1.37b	1.56a

Means with different letters in horizontal order are statistically different ($p<0.05$); $p<0.01$).

So, results obtained in both cutting intervals indicate that 30-days cutting interval is a short time to expect in this crop a significant response to nitrogen fertilizer. According the results is observed a time variation between cut intervals (30 and 60-

days), originate chemical composition differences as natural consequence of the plant maturity stage at 60-days.

3.3.2 Gross nitrogen dynamic

For N applied is important to clarify that the applied quantity per year was adjusted to cutting interval, then, the move frequent was the cut, the move frequent was the N application. Nitrogen uptake was similar for the three treatments under 30-days cut interval, indicating that the N concentration and biomass production per treatment were not enough to have influence (Table 3.5). These results show again the explained for biomass production results, where 30-days of cut interval was not enough time to get statistical differences between treatments. Besides, the significant difference ($p<0.01$) in N concentration for the treatment with highest N fertilizer denoted a low difference in N concentration.

The results of N use efficiency (NUE) for the treatments indicate a positive response for the cut interval of 60-days, while for the cut interval of 30-days the fertilization did not have any effect (Table 5). The N recovery efficiency (NRE) showed that N fertilization was not effective in the 30-days cut interval (Table 5). However, in the 60-days cut interval, the pasture recovered 40% and 45% for the treatments of 250, and 500 kg N ha⁻¹year⁻¹, respectively. The leaching analysis for the 60-days cut interval indicated lower N leached in the treatment of 500 kg N ha⁻¹year⁻¹, so, the total N leached was 1.2% of the total N applied (Table 5). In the case of the treatment with 250 kg N ha⁻¹year⁻¹, N leached was equivalent to 9.5%.

The gaseous N losses (GNL) analysis showed that most of the fertilized nitrogen losses occur through volatilization. For the 250 and 500 kg N ha⁻¹year⁻¹ treatment, 22.8, and 44.5 kg N ha⁻¹ were lost during the experiment, which is equivalent to 13.6 and 13.3% of the total nitrogen applied, respectively.

Table 3.5. Nitrogen applied, N uptake, N use efficiency, N recovery efficiency and N leaching for Napier grass per treatment and cut intervals.

Cut Int. / Treatment	0 kg N	250 kg N	500 kg N
N applied ($\text{kg ha}^{-1}\text{cut}^{-1}$)			
30-days	-	20.80	41.70
60-days	-	41.70	83.40
N uptake ($\text{kg N ha}^{-1}\text{cut}^{-1}$)			
30-days	35.7	34.9	39.2
60-days	54.1	70.6	91.9
N use efficiency ($\text{kg DM kg}^{-1}\text{N}$)			
30-days	-	-1.73	1.20
60-days	-	17.27	17.51
N recovery efficiency (%)			
30-days	-	-4	8
60-days	-	40	45
N leaching (kg N ha^{-1})			
30-days	-	15.71	3.24
60-days	-	16.14	4.59

The gross N balance calculation showed that Napier grass is a crop with a high N requirement (Table 6). For the Control treatment, the nitrogen uptake for 30-days cut interval was 25% greater than the 60-days cut interval, while in the case of the lower N fertilizer treatment the difference was 1% in favour of the longest cut interval. For the highest N fertilization treatment, there was a clear significant difference between cut intervals, and the N uptake was higher for the 60-days cut than for the 30-days cut interval, as a consequence of the greater biomass production.

Table 3.6. Nitrogen application, plant uptake, and balance (including Nitrogen deposition, leaching and emission) of Napier grass under two cut intervals.

Cut Int. / Treatment	0 kg N	250 kg N	500 kg N
N applied (kg ha ⁻¹)			
30-days	0	167	334
60-days	0	167	334
N uptake (kg ha ⁻¹)			
30-days	286	279	313
60-days	216	282	368
Balance (kg N ha ⁻¹)			
30-days	-281	-146	-22
60-days	-211	-149	-78

3.4 Discussion

The difference in temperature between the mean of the five hottest months and the mean of the three coldest months was 5°C. This amount caused a considerable change in growth and development of Napier grass. The observed effects are in agreement with Sweeney and Hopkinson (1975) who determined 30 – 35°C as the optimum mean daily temperature for biomass production of C₄ grasses. Growth is severely affected when the temperature is under 20°C. During the experiment, the three coldest months registered monthly minimum temperatures of 15°C, while the mean was in the order of 21.1°C. Ferraris *et al.* (1986), in a controlled environment, found that the day/night temperature optimum for biomass production of Napier grass is 33/28°C. Sweeney and Hopkinson (1975), in a similar environment, determined an optimum day/night temperature of 30/25°C for six tropical grasses that included *Chloris gayana*, *Melinis minutiflorum*, *Brachiaria ruziziensis*, *Cenchrus ciliaris*, *Brachiaria mutica*, and *Panicum maximum*. However, the temperature oscillation (5°C) applied in these two experiments (Sweeney and Hopkinson, 1975; Ferraris *et al.*, 1986) does not reflect the reality of many tropical areas, where the variation between day/night temperature is equal to or greater than 10°C.

The growth rate and its relation with the temperature decline during the three coldest months indicate that during this period the pasture biomass production decreased $33 \text{ kg DM ha}^{-1}\text{d}^{-1}$, which it is equivalent to 45, 38, and 34% in reduction for each of the treatments. These results are coincident with values found by Ivory and Whiteman (1978) for Kikuyu grass, which values fitted a polynomial relation for growth rate considering the day/night temperature variation, showing a difference of 40%. The last appreciation is supported by McWilliam (1978), who states that growth rate is more sensitive to temperature stress than photosynthesis, which has a broad temperature optimum.

The largest amount of biomass accumulated during the experimental period was $23.6 \text{ t DM ha}^{-1}$, which translates to a biomass yield of more than 30 t year^{-1} . This result is similar to the results obtained by others who showed that annual yields varied from 20 to 50 t (Costas and Chadler, 1961; Ferraris and Sinclair, 1980; Ferraris *et al.*, 1986; Kubota *et al.*, 1994; Andrade *et al.*, 2000; Tudsri *et al.*, 2002).

During the hot season, the ratio of dry matter in Napier grass increased rapidly due to the growth dynamics of the plant as an effect of temperature and radiation. The stem is the structure where the fiber concentration is constantly increasing. It is possible to observe this effect in the value of the leaf – stem ratio distribution between cut intervals, which reflects the building of dry matter constituents, such as the effect of plant age. As consequence of the plant maturation the fibrous matter increases per accumulation of lignin or cellulose (Johnson *et al.*, 1973).

Tillering responded to the cold season by increasing the number of stems. The performance of Napier is similar to that of Rhodes and Kikuyu grasses (Ivory and Whiteman, 1978), which were evaluated with lower day temperatures under controlled conditions. Ferraris and Sinclair (1980) working with Napier grass in a similar latitude ($17^{\circ}38'' \text{ S}$, Queensland, Australia) to the one of this experiment, found a similar tendency in this pasture. The tiller population increased during the cold season, e.g., from May to August, and started to decrease again during the beginning of September. However, Napier grass showed that the positive response of the tiller population to lower temperature is opposite to growth. Hence, the increased number of stems does not mean larger biomass production, and this performance is

similar to several temperate species (Langer, 1963). This characteristic change is depend on the grass species. In many tropical grasses the optimum temperature for tillering is similar to the optimum temperature for growth (Jozwik, 1970; Wilson & Ford, 1971).

Plant elongation is a variable which reflects the plant's vertical response to the environmental conditions, e.g., soil and climate. Ferraris *et al.* (1986) indicated that the pattern of change in plant height was an initial phase of slow elongation lasting about four weeks, followed by rapid elongation. However, in the present experiment, the 30-days cutting interval presented a greater elongation rate than the 60-days cutting interval. However, it did not have relationship with the production in biomass. Ferraris *et al.* (1986) found that the elongation rate reached a maximum between 27/22°C and 33/28°C of day/night temperature, with a maximum of 2.9 cm day⁻¹, which decreased to 1.7 cm day⁻¹, when the day/night temperature decreased to 21/16°C. This means that the temperature effect was in the order of 0.2 cm day⁻¹ per °C of temperature variation. This value is in agreement with the values determined in the present experiment (Table 3.3). Cruz and Boval (2000) showed that the internode elongation rate may increase with nitrogen availability. In the present experiment, all the elongation rate means (from 2.54 to 3.07 cm day⁻¹), including the control elongation rate, were larger those reported for Napier grass by Muia *et al.* (1999), who determined values from 1.64 to 0.91 cm day⁻¹, applying 1200 and 800 mm of water.

In the case of the leaf appearance rate, the increase of 20% per 1 °C indicates that results are in agreement with the concept that this variable is very sensitive to temperature change (Kleinendorst and Brouwer, 1970; Nelson, 2000). However, the differences in consecutive sheath lengths can considerably diverge leaf appearance rate values (Duru and Ducrocq, 2000). For example, in relation to the effect determined for nitrogen fertilization, Cruz and Boval (2000) suggest that the increases observed in leaf appearance rate with nitrogen availability for some tropical species with ability to elongate their internodes, may be the result of the high sensitivity of internode elongation rate to nitrogen availability.

Leaf length, which is dependent upon the rate of leaf elongation, is mainly affected by the amount of resources available to the plant, especially nitrogen, moisture, and temperature (Gastal and Durand, 2000; Lemaire and Agnusdei, 2000). In *Brachiaria decumbens*, Busqué (2001) determined that the leaf elongation rate was the leaf growth morphogenetic variable that was most sensitive to temperature and nitrogen fertilization. The highest value was obtained at 30°C with the highest level of nitrogen fertilization. This result is similar to the value found by Murtagh *et al.* (1987) in *Pennisetum clandestinum*, which had an optimum temperature for leaf elongation rate of 30°C. In the present experiment, Napier grass responded to both temperature and N fertilization, and the mean leaf size in the 60-days cutting interval with the highest N level was 9.4% greater than the control treatment. However, this difference did not affect the leaf–stem ratio, as control or 0 kg N had the highest proportion of leaves.

The negative relationship between yield and nutrient composition is well documented and has been recorded elsewhere for Napier grass (Andrade and Gomide, 1971). Johnson *et al.* (1973) demonstrated that the N content is inversely related to the deposition of dry matter constituents, such as lignin or cellulose. This effect is very clear in the present study, when the values between cut intervals are compared. However, the fertilization effect had an important role, not only because it promoted greater biomass production but also because it increased the N contained in the total biomass, which surpassed the better leaf – stem ratio observed in the Control treatment. The nitrogen use efficiency was calculated to determine the fertilizer effect for improving biomass production in order to justify the biological and economic viability of nitrogen fertilizer programmes for Napier grass management in the dairy production systems of the studied area. In agreement with the local price of nitrogen (0.9 dollars kg⁻¹ N), which is imported as urea, and the NUE, it is possible to profit the viability to use N fertilizer in Napier grass, but considering the new principles for inorganic fertilization and doses, and crop management defined in the present experiment. Nevertheless, the NUE in Napier grass could increase depending on the initial N concentration in the soil. The soil of the experimental area had just been characterized to plant the pasture, and the soil had a high initial N concentration (0.21%). In many cases, land use and the pasture age have strong impact on NUE.

For example, Gargano *et al.* (2000) obtained a NUE that was 30% higher than this experiment in *Digitaria eriantha*, established four years earlier.

The NRE (%) for the 30-days cutting interval was inadequate to recover the N included as fertilizer. From an economic and environmental point of view, this cut interval is not appropriate. In maize, profitable agricultural production is obtained when the NRE is among 40 to 50%, which will occur when the temperature and moisture conditions are in optimal conditions (Oberle and Keeney, 1990). In Napier grass, for the 60-days cut interval the range was between 40 to 45%. Therefore, at this cut frequency the N fertilizer was absorbed in a high proportion by the pasture, reducing leaching losses, contamination of groundwater quality, and other problems caused when there is an inefficient N use (Sharpe *et al.*, 1988). In agreement with NUE and NRE, the implementation of a N fertilizer programmes for Napier grass under cut and carry system is advisable to cut the Napier pasture in physiology stage over 50 days.

The N leaching losses were very little for the treatment with the largest N dose in the two cut intervals, while in the lower fertilization level, the leaching increased more than 8%. However, these results are contradictory with Owen *et al.* (2003), who stated that when the N dose is greater, the N leaching tends to be higher. The equation that was applied to determine N leaching (Willigen, 2000), emphasizes the N balance between application and uptake, which are the determinant factors to increase or decrease the total N leaching.

The gross GNL calculated through the equation proposed by IFA/FAO (2001) indicates a slightly proportional variation among treatments, because the GNL depends of the quantity of fertilizer applied. So, while the N dose is greater, the GNL increases proportionally, independently of the application frequency.

The N balance in the treatment with lower N application showed that 48% of the N uptake was from the soil, while in the case of the largest dosage, it still extracted 21% of the N available in the soil. This means that 500 kg N ha⁻¹ year⁻¹, or 83 kg N per application covers only 65% of the total N uptake by the pasture. This is a clear explanation of the fast deflection of soil fertility in areas cropped with Napier grass,

which did not receive any fertilizer, either organic or inorganic. In general, Napier grass yield is high soon after establishment, which may be attributed to the increased mineralization of organic N in the soil induced by land cultivation, but soon thereafter production starts declining (Mwangi, 1999).

Finally, based on the performance of Napier grass in this experiment, it is possible to recommend the application of N fertilizer in Napier grass if the farmer applies the amount of N fertilizer and crop management as defined in the present experiment.

3.5 Conclusions

In this experiment we found that the temperature changes between the hot and cold seasons impacted the physiology of Napier grass with effects on forage production. The response of Napier grass per kg of N applied had the same relation in the two fertilizer treatments. From the point of view of biomass production and N use efficiency, the cut interval of 60-days is more advisable for cut and carry systems than the cut interval of 30-days. Therefore, the cut frequency is an important factor for improving the N-budget of a smallholder's farmer field where Napier grass is being grown.

For the 60-days cutting interval, although it had the best NUE, even the highest level of N fertilizer was insufficient to cover the N uptake of Napier grass. This means that the N dose should be increased by 37% to maintain the N-balance, considering any variation in the obtained biomass production. This experiment confirmed that there is a good potential to cultivate Napier grass in the dairy basin of Santa Cruz, Bolivia, considering the biomass production that was obtained in this experiment.

Abstract

Napier grass (*Pennisetum purpureum* Schum.) is one of the most commonly-used forages for feeding of livestock, including cattle, goats, sheep, horses and fish, especially in tropical environments. In many cases the forage yield of this crop is below its yield potential due to poor management and environmental limitations. The important role of this crop as a forage and its current yield limitations suggest the need for the development of a decision support tool that can help improve local management. A dynamic crop simulation model offers an alternative to provide options for sustainable forage production. The objective of this study was to adapt the simulation model CROPGRO for Napier grass crop and to incorporate it into the Decision Support System for Agrotechnology Transfer (DSSAT). Model development was based on a detailed review of literature of known Napier physiology and experimental data to provide a structured and quantitative framework for describing crop response to environment and management. The species, cultivar and ecotype files that determine the genotypic information were created based first on literature information and secondly on optimisation with field data and model calibration. The first version of the Napier grass model had a Root Square Mean Error (RMSE) of 29, 29, 20, 15, and 5% for aboveground biomass, leaf weight, stem weight, leaf number per stem and plant height, respectively, while the Index of Agreement (d) for the same variables was 0.97, 0.92, 0.99, 0.95, and 0.99, respectively. This chapter presents the inclusion of the Napier grass model into the Cropping System Model (CSM)-CROPGRO Version 4.0 framework, confirming that the new crop model has good potential to assess management strategies for optimising forage production of Napier grass.

4.1 Introduction

Napier grass (*Pennisetum purpureum* Schum.) is a C₄ grass species that originated in eastern and central Africa (Boonman, 1993). Nowadays it is one of the most widely used grasses for feeding of livestock, including cattle (Mwangi, 1999; Kariuki *et al.*, 1998; Vilela, 1990; Ruiz *et al.*, 1992; Sollenberger and Jones, 1989; Anindo and Potter, 1986), goats (Richards *et al.*, 1994), sheep (Larbi *et al.*, 1991) and horses (Ferreira *et al.*, 1995). In addition, it is also grown as a barrier to control soil erosion (Owino & Gretzmacher, 2002), for paper pulp fibre (Ferraris and Sinclair, 1980), renewable energy (Woodard *et al.*, 1993), and to feed various species of fish (Chikafumbwa, 1996). Its high potential productivity and adaptability to a broad range of climatic and soil characteristics are one of the main reasons for its wide distribution and utilization as forage for a wide range of environments, ranging from sea level up to an elevation of 2000 m (Van de Wouw *et al.* 1999). For instance in southeast Asia in areas with high human and animal population, which is the main characteristic of the agricultural production systems, cut and carry systems provide the majority of the fodder supply (Semali, 1988).

In Bolivia the area in Napier grass production has expanded since the early 1970's. However, only during the last ten years has its use expanded, mainly for feeding of milking cows in a cut and carry system. A survey of a 5% sample of the 7000 farmers located in the dairy basin of Santa Cruz conducted in 1997 found that approximately 25% of these farms used Napier grass as a feed resource (Herrero *et al.* 2000).

However, farmers have experienced many limitations in the management of Napier grass. For example, farmers do not control the age at which the grass is cut and frequently they cut the grass at an inadequate age, such as too early or too late when it is overmature. In addition, the high biomass production causes problems with soil fertility. In other cases, farmers do not grow Napier grass during the rainy season because they consider that forage intake during grazing is enough to cover the forage requirement of their cows. They also use the mature forage during the dry season when the Napier plant has a high fibre composition and its nutritional quality is poor.

Local research with lactating and dry cows that graze various *Brachiaria* species (*B. decumbens* and *B. mutica*) found a low voluntary intake and poor forage quality during the rainy and dry seasons. As a result lactating cows that graze only and do not have any supplemental feed will not produce more than 3 to 4 kg of milk day⁻¹ (Joaquin and Herrero, 2001). Napier grass, therefore, can be a strategic feed resource for improvement of forage intake and elimination of forage deficit during the dry season in the main dairy production region of Santa Cruz, Bolivia (Joaquin *et al.*, 2002). However, Napier is a crop that has not been used to its full potential due to a lack of knowledge of the crop's management, not only fertilization practices but also harvesting practices such as an adequate cutting age, causing its long-term production to be unsustainable. Similar limitations in Napier grass management have been found in many other countries where Napier is an important forage grass, especially in South America, Africa and Asia (Alves dos Santos *et al.*, 2001; Deschamps and Alves de Brito, 2001; Muia *et al.*, 1999; Kubota *et al.*, 1994).

The ability of crop simulation models to predict growth and development as a function of soil and weather conditions, agronomic practices and cultivar traits makes such models attractive tools for crop improvement and crop management (Whisler *et al.*, 1986; Tsuji *et al.*, 1998; White, 1998). The use and application of crop simulation models has increased during the last 10 years. They can be applied and used by farmers for strategic as well as for tactical decision making and by researchers and research managers as a research tool to help identify knowledge gaps (Hoogenboom, 1996; 2000). For the specific case of pastures, a simulation model is an option to improve pasture management because it can provide answers to such questions as “what would happen to forage yield and quality if more fertilizer were applied, or if the crop was grown at another location with different weather and soil conditions?” (Bouma, 1997). The Decision Support System for Agrotechnology Transfer (DSSAT) is a computer system that includes crop models for simulating growth and development for more than 20 crops (Hoogenboom *et al.*, 2004). It has demonstrated a high reliability under different climates, soils and management conditions (Jones *et al.*, 2003). Using the DSSAT program it is possible to: a) organize and file databases for climate, soils, crops, experiments, and prices; b) simulate crop production for one or more periods and sequences; c) analyse results

and graphically present simulations; d) evaluate different management practices, specific to a farm or one of its components (Jones, 1993; Jones *et al.*, 1998). Furthermore, once the models have been evaluated with local data, they can provide support for planning decisions in research and technology transfer and identify policies for intervention (Bouma, 1998).

Several models have been developed that simulate pasture growth, including Blue grama (Hanson *et al.* 1985), Century (Parton *et al.*, 1993), GRASMOD (Van de Ven, 1992), GRASP (McKeon *et al.*, 1990), GRAZPLAN (Moore *et al.*, 1991) and the HURLEY PASTURE (Thornley and Verberne 1989; Thornley and Cannell, 2000) models. In some cases models have been combined or modified to improve simulation of pasture and forages (Gijsman *et al.*, 1999; 2002). For instance, the Bahia grass (*Paspalum notatum*) (Boote *et al.* 2003) and Brachiaria (Giraldo *et al.*, 1998) models were incorporated into DSSAT by using the CROPGRO model as a template. CROPGRO predicts yield and yield components for several dicotyledonous plants, including soybean, peanut and common bean. Rymph *et al.* (2004) emphasized the physiological parameters of grasses and adapted the CROPGRO model to predict growth and composition of tropical grasses. Based on past experience in the development of a model for Bahia grass and Brachiaria, CROPGRO was selected as a model template for the development of a Napier grass model. Development of a new plant growth model is described in detail by Hoogenboom (1996; 2003), who emphasizes the difference between user-supplied parameters and model-supplied parameters.

4.2 Model description

DSSAT is a comprehensive decision support system for assessing agricultural management options (Tsuiji *et al.*, 1998). The functions of DSSAT were selected primarily to support the use of crop simulation model in decision making applications. The utility of this system depends on the ability of the crop models to provide realistic estimates of crop performance for a wide range of environment and management conditions (Jones *et al.*, 1998). The CROPGRO model is a generic crop module that is part of DSSAT Version V4.0 and is based on the SOYGRO,

PNUTGRO, and BEANGRO models (Boote *et al.*, 1998). The CROPGRO model is process-oriented and considers the crop carbon balance, crop and soil N balance, and the soil and plant water balance (Boote *et al.*, 1998; Ritchie *et al.*, 1998). It includes detailed plant physiological variables that define the genotypic parameters to differentiate species, ecotype and cultivar responses. Furthermore, CROPGRO can be easily modified to predict yield of various other crops as a function of environmental conditions and management scenarios (Hoogenboom, 1996). CROPGRO has been evaluated for current environmental conditions and management practices (Jones and Ritchie, 1991; Egli and Brunening, 1992; Hoogenboom *et al.*, 1992; Nagarajan *et al.*, 1993), but also has been used to project the impact of future changes in climatic conditions in the USA and many other countries on agricultural production (Curry *et al.* 1995; Pickering *et al.*, 1995).

For all species that are simulated with the CROPGRO model, there is one set of common FORTRAN code, while all attributes associated with each individual species, such as dry bean, peanut, and soybean, are defined in external data files that are called species files. The species (SPE) file contains those parameters that represent the species' physiological response across all environments. This includes a species or crop's basic tissue composition for stems, leaves, and roots, and functions that describe processes such as photosynthesis, growth and maintenance respiration, carbon partitioning and growth, senescence, N-assimilation and phenological development, as well as the sensitivity of these processes to environmental factors, especially temperature, solar radiation, photoperiod and drought and nitrogen stresses. Parameters that define the unique characteristics of each cultivar are described in a cultivar (CUL) file that provides information on photothermal days, the time to first flower, first seed, or first pod, and time to maturity. The file also contains the maximum photosynthetic rate of a leaf, maximum leaf size and specific leaf area. In total there are 15 traits per cultivar. The ecotype (ECO) file contains genetic attributes that are descriptive of broad categories of cultivars, such as seed size for common bean or photoperiod sensitivity for soybean (Hoogenboom, 1993; Hoogenboom, 1996; Boote *et al.*, 1998).

The growth environment is described by the SOIL and WEATHER files. The soil file provides parameters for soil physical and chemical characteristic. The weather file contains daily maximum and minimum temperature, solar radiation, and rainfall. The WEATHERMAN program in DSSAT enables users to reformat weather data and to create files that are compatible with the DSSAT models, fill in missing data, generate weather data, compute statistics, and graph weather data (Pickering *et al.*, 1994; Jones *et al.*, 1998).

Crop management information is stored in FileX; it is used to document an experiment and also provides input for the crop models (Imamura *et al.*, 1994). It includes a general description of the experiment, irrigation, fertilizer, residue, tillage and harvest management and cultivar and other information. These files also provide a link to the cultivar and species genetic coefficient files as well as the weather and soil files (Jones *et al.*, 1998). Observed data are stored in FileT; it includes biomass of all plant components that can be measured during the growing season, leaf area index and other related information.

Crop development in CROPGRO uses a flexible approach that allows for the development process during the various growth phases to be differentially sensitive to temperature, photoperiod, water deficit, and N stresses. There are up to thirteen phases, each having its own unique developmental accumulator that starts at the endpoint of a reference growth stage and terminates when the photothermal units have been accumulated as defined in either the cultivar or ecotype file. The physiological development rate for any one day of a developmental phase is typically a function of temperature, photoperiod, and water deficit (Boote *et al.*, 1998; Boote *et al.*, 2003).

The growth environment of a crop is defined by the local soil and weather files that are required as an input for the model. The soil file includes parameters that define a soil profile's physical and chemical characteristics and structure. The soil profile is defined based on the original soil horizons, but is divided into computational layers for the calculation of the soil water balance, as described by Ritchie (1985). For each layer, daily changes in soil moisture content are the result of infiltration, soil evaporation, crop transpiration and downward movement to the lower layer.

Precipitation is a daily input. Runoff is a function of soil type, soil moisture content and precipitation.

4.3 Materials and methods

4.3.1 Soil and climate characteristics

A Napier grass experiment was conducted at the Estación Experimental Agrícola of Saavedra (EEAS - CIAT) from 2001 to 2002. The latitude of the EEAS is 17.14°S, the longitude is 63.10°W, and the elevation is 320 m.a.s.l. The monthly mean temperatures for the last 47 years showed that the coolest months are June and July, with an average daily temperature of 20.2°C, and the hottest months are December and January, with an average daily temperature of 25.8°C. The annual mean precipitation is 1365 mm; the wettest month is January, with a total rainfall of 224 mm, and the driest month is July, with a total rainfall of 42 mm (Busqué and Herrero, 2001).

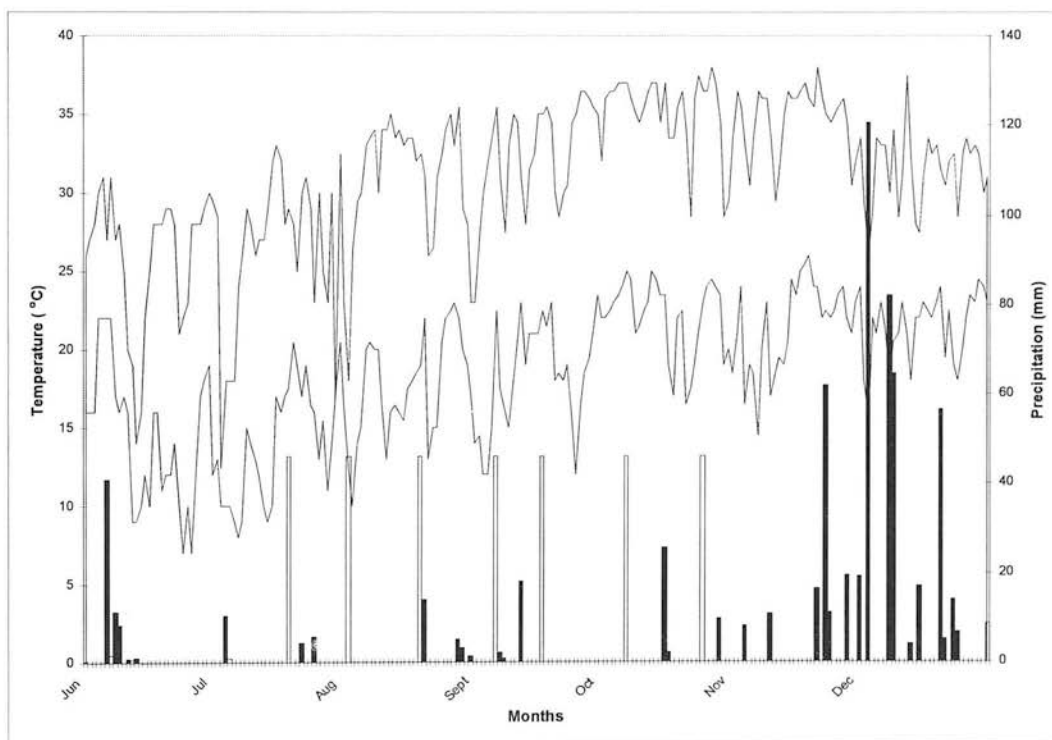


Figure 4.1. Minimum and maximum mean daily temperature (lines), precipitation (black bars) and irrigation (white bars) from June to December 2002 for the experimental site.

During the experimental period, daily maximum and minimum temperature, radiation, precipitation and irrigation were recorded by a weather station that was located at approximately 1000 m from the experimental site.

The soil classification indicates that the soil had an alluvial origin, corresponding to the Inceptisol order (Orellana *et al.*, 1990). At the start of the study the soil profile was characterized to a depth of 100 cm. Soil texture was classified as loam in the top and sandy loam in the bottom layers. In the top layer, the nitrogen concentration was 13.7 g kg^{-1} , pH (H_2O) was 6.4, organic carbon was 0.75%, and the bulk density was $1.53 \text{ cm}^3 \text{ g}^{-1}$.

4.3.2 Crop management

In this experiment the response of Napier grass (c.v. Taiwan) to various nitrogen fertilizer treatments at different physiological stages was evaluated. The assessment was conducted during the spring season from October to December, 2002 and data collection lasted for a period of 80 days. Three treatments with three repetitions were monitored. An area of 1 m^2 (1 plant) per plot was sampled every 10-days, beginning at 10 days after the start of the experiment and the first fertiliser application.

The crop was established with vegetative material three months prior to the start of the evaluation. Two stems with three nodes each were planted per hole to obtain a plant. At the start of the present experiment, the grass was cut to a height of 0.5 cm above the ground. The experiment included three nitrogen application treatments: Control (no nitrogen), 250 and $500 \text{ kg N ha}^{-1} \text{ year}^{-1}$. The actual amount of N that was applied for each application was calculated based on a 60-day cutting interval. This corresponded to amounts of 0 (control), 41.5 and 83 kg of N per application. Because the total experimental period had duration of 80-days; a second N application was conducted at 60-days after the start of the experiment. Because the experiment was conducted during dry season, it was necessary to irrigate seven times at an approximate rate of 46 mm per application. However, the infrastructure limitations for irrigation caused some difficulties in irrigation scheduling and measuring the total amount of water that was applied.

4.3.3 Plant variable measurements

A total of eight growth analysis samples were collected over a period of 80 days. The variables that were measured included plant height (cm), leaf weight (kg DM ha^{-1}), stem weight (kg DM ha^{-1}) and weight of total aboveground biomass (kg DM ha^{-1}). In addition, the leaf nitrogen concentration (%), stem nitrogen concentration (%) and total nitrogen uptake (kg N ha^{-1}) were determined. Plant height was measured with a large ruler; ten measurements were taken per individual plant that was monitored, for a total of 40 measurements per plot. Each plant was cut at 8 cm above the ground for further analysis. Five tillers from each plant were sub-sampled to assess the individual plant components, including leaf weight, stem weight and nitrogen concentration. Leaf and stem structures were separated and the green matter was oven dried at 65°C to a constant weight to determine dry matter.



Figure 4.2. Experimental area for Napier grass physiology characterization.

4.4 Model development

The CSM-CROPGRO model included in DSSAT Version 4.0 (Jones *et al.* 2003; Hoogenboom *et al.*, 2004) was used to develop the structure of the Napier grass model. The genotype files, including the species, cultivar and ecotype files of the Brachiaria and Bahia grass (*Paspalum notatum*) models were used as a template. In addition, some coefficients of the sugar cane (*Saccharum officinarum*) model were also used.

In the species file (SPE) (Table 4.1.), for *Photosynthesis*, the parameters PARMAX (Value of maximum photosynthetic active radiation) and PHTMAX (Maximum amount of CH₂O which can be produced if PAR is very high) were defined with the calibration process. The values for FNPGT (Critical values of temperature [°C] for the function to reduce canopy photosynthesis under non-optimal temperature on canopy level photosynthesis) were defined according to Ivory and Whiteman (1978).

The values for the *Plant composition parameters* were calibrated based on known information of Napier grass (Ivory and Witheman, 1978; Reed *et al.*, 2000; Hilbert and Reynolds, 1991; Deschamps and Alves de Brito, 2001). During this process, the values for PROLFI (Maximum protein concentration in leaves), PROLFG (normal growth protein composition in leaves), PROLFF (minimum leaf protein composition) in leaves structure and PROSTI (Maximum protein concentration in stems), PROSTG (normal growth protein composition in stems) and PROSTF (minimum leaf protein composition in stems) for stem structure were further adjusted.

Calibration was also conducted for the *Vegetative partitioning parameters*, XLEAF (leaf growth) and YLEAF values (stem growth) were adjusted by minimizing the error between observed and simulated leaf and stem biomass. For the *Phenology parameters*, the minimum, medium (optimal range) and maximum temperature were obtained from references for Napier grass (Ivory and Whiteman, 1978; Ludlow and Wilson, 1971). For the *Root parameters*, only the value for RFAC1 coefficient (root length density) was changed. It was based on sugarcane, considering that the canopy and root structure of Napier and sugarcane are very

similar. For the *Canopy height and width growth parameters* the variables YVSHT and YVSWH were calibrated, while the values for XHWPARG were obtained from Ivory and Witheman (1978).

Table 4.1. Species parameters for Napier grass used in the CROPGRO model.

PARAMETER	VALUE	UNIT
<u>Photosynthesis</u>		
PARMAX	65	mol PFD m ⁻² d ⁻¹
PHTMAX	120	g CH ₂ O m ⁻² d ⁻¹
FNPGT	6.7, 24, 36.7, 58.5	°C
XLMAXT	0.0, 6.7, 24, 37, 47, 59	°C
<u>Plant composition</u>		
PROLFI, PROLFG, PROLFF	0.175, 0.127, 0.06	g(prot)/g(leaf)
PROSTI, PROSTG, PROSTF	0.156, 0.093, 0.05	g(prot)/g(stem)
<u>Vegetative partitioning</u>		
YLEAF	0.65, 0.65, 0.55, 0.55, 0.5, 0.45, 0.3, 0.3	
YSTEM	0.15, 0.15, 0.2, 0.25, 0.35, 0.45, 0.6, 0.6	
<u>Leaf growth</u>		
FINREF, SLAREF, SIZREF	500, 350, 600	cm ² g ⁻¹ , cm ² /leaf
SLAMAX, SLAMIN	750, 200	cm ² /g
SLAPAR, TURSLA	-0.048, 1.5	%
XVGROW (1-6)	0.0, 5.0, 10.0, 15.0, 20.0, 25.0	cm ²
YVREF (1-6)	0.0, 205, 772, 1160, 1506, 1980	cm ²
XSLATM (1-5)	-5.0, 6.7, 24.0, 36.7, 58.5	°C
<u>Roots</u>		
RFAC1	5500	cm/g root
<u>Phenology</u>		
Vegetative development	6.7, 27.5, 37.5, 58.5	°C

*Canopy height and width
growth*

YVSHT(1–10)	0.022, 0.031, 0.126, 0.156, 0.163, 0.163, 0.167, 0.173, 0.18, 0.191	m/node
YVSWH(1–10)	0.02, 0.029, 0.124, 0.154, 0.161, 0.161, 0.165, 0.171, 0.178, 0.0	m/node
XHWTEM	8.0, 20.0, 30.0 35.0, 50.0	°C

In the ecotype (ECO) file, the value for TRIFL (Rate of appearance of leaves on the main stem) was changed to 0.18 leaves/thermal day based on experimental observations.

In the cultivar (CUL) file several parameters were changed, including LFMAX (Maximum leaf photosynthesis rate), which was defined as $2.5 \text{ mg CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$, SLAVR (Specific leaf area of cultivar under standard growth conditions), which was calibrated as $350 \text{ cm}^2 \text{ g}^{-1}$ and SIZLF (Maximum size of full leaf), which was calibrated as 230 cm^2 .

As a normal procedure for the calibration of crop models, the physiological coefficients were adjusted using the Root Square Mean Error value (RMSE). It provides a measure (%) of the relative difference among simulated and observed data. The simulation is considered excellent with $\text{RMSE} < 10\%$, good if $10 - 20\%$, fair if $20 - 30\%$ and poor if $> 30\%$ (Loague and Green, 1991). The value for the d-statistic is an indication of the Index of Agreement. The closer this index is to one, the better the agreement between the two variables that are being compared. If the index approaches zero, there is a poor correspondence between the two variables that are being compared (Willmott *et al.*, 1985).

4.5 Sensitivity analysis

The sensitivity analysis of parameters or inputs is the second step following model calibration. The method used for the sensitivity analysis is based on the increase or decrease of parameter values over a broad range and results in a description of the impact of a single parameter on model behaviour (Zalud and Stastna, 2000). The

sensitivity analysis was based on the real weather data that were used for model calibration. The first analysis included the sensitivity of the model to systematic changes in temperature. This was conducted by applying six different temperature regimes, consisting of an increase or decrease in temperature of +1, +2, +3°C, -1, -2 and -3°C, respectively, of the real maximum and minimum temperature data recorded during the experiment and used for model calibration. A second sensitivity analysis was conducted to assess the response of Napier grass to three different levels of nitrogen application: 125, 375 and 625 kg N ha⁻¹year⁻¹, applied every 60 days. Two levels, i.e., 125 and 375 kg N ha⁻¹year⁻¹ were defined as intermediate values in relation to the two original fertilizer treatments, i.e., 250 and 500 kg N ha⁻¹year⁻¹, of the actual experiment and one level was added above the highest level, i.e., 625kg N ha⁻¹year⁻¹.

4.6 Results and discussion

During the experimental evaluation period the average maximum and minimum temperatures were 34°C and 21.6°C, respectively, while total precipitation was 472 mm (Figure 2.1).

4.6.1 Aboveground biomass

The comparison of the simulated and observed data for the first six growth analysis samplings from the 10 to the 60-days showed that the simulated values were higher than the observed data. However, for the final harvest at 80-days after the start of the experiment the model under-predicted total aboveground biomass (Figure 4.3). The over-prediction by the model could express the natural high growth potential of Napier grass. It is also possible that the crop growth was not completely manifested due to limitations of available nitrogen and especially water through precipitation and supplemental irrigation, considering that most of the experimental period was during the dry season (Figure 2.1). In general, Napier grass is a crop that shows a wide variation in production and performance. In a review for biomass production, values ranged from 10 to 40 t/ha hectare per year (Wouters, 1987; Skerman and Cameron, 1990; Schreuder *et al.*, 1993; Boonman, 1993; Anindo and Potter, 1994;

Humphreys, 1994). However, under good soil and environmental condition this Napier grass has a high potential to accumulate biomass.

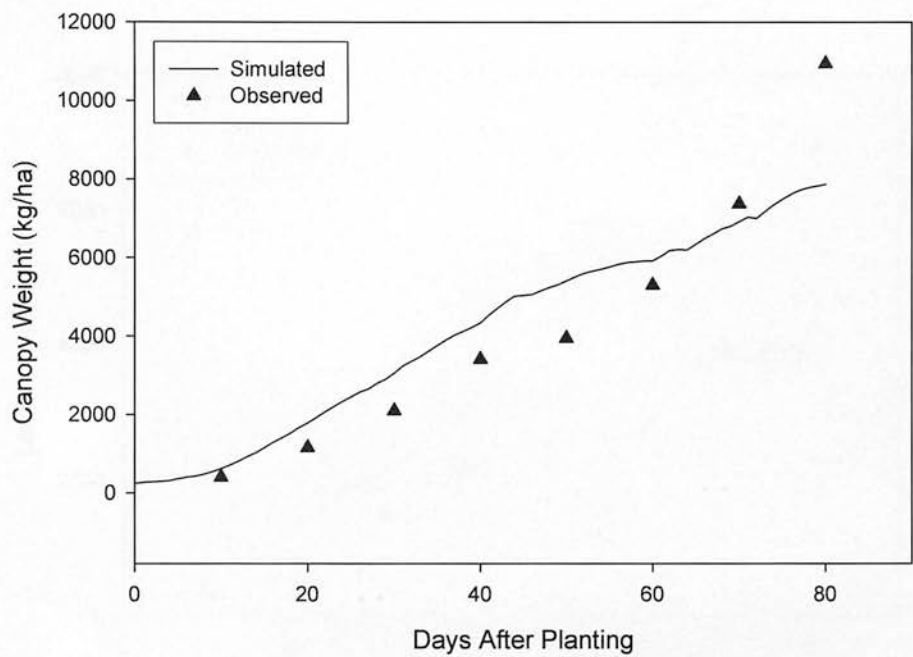


Figure 4.3. Simulated (line) and observed (point) data for aboveground biomass (Top) for Napier grass harvested at 10-days cutting interval.

The strong increase in biomass production found in the observed data at the 70 and 80-days could also have been caused by the second fertilizer application and the rain that occurred a few days before the 70-days sampling, causing a boost in growth (Figure 4.1). The over-prediction during the first growth phase and the under-prediction for the last sampling resulted in a fair RMSE (29%). However, the Index of Agreement was high (0.97).

4.6.2 Leaf and stem weight

Leaf and stem weight are the components which summarize total aboveground biomass. Leaf weight was over-estimated during the first 60-days of the experimental period and a decrease in growth during the final sampling period when compared to the observed data (Figure 4.4). This could be caused by the fact that the model predicted leaf senescence, causing a decrease in green leaf biomass. This variable

was not measured in the observed, as dead or mature leaves were not separated from green and active leaves during the sampling process. This could also have impacted total aboveground biomass, as mentioned previously.

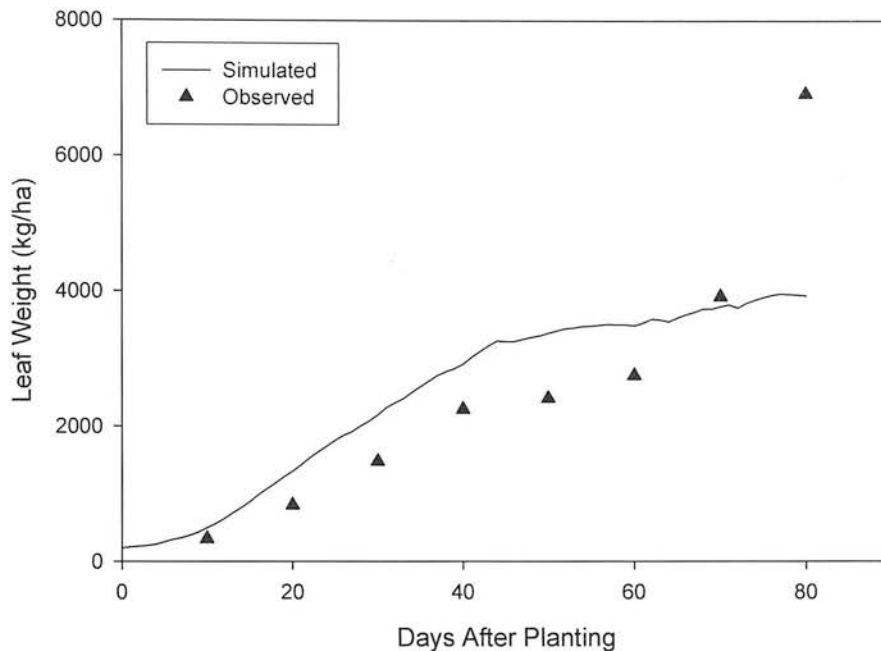


Figure 4.4. Simulated (line) and observed (point) and leaf weight for Napier grass harvested at 10-days cutting interval.

Leaf production showed over-prediction during the first growth phase and an under-prediction from 20 to 60-days, which resulted in a fair value for RMSE (29%). The Index of Agreement was acceptable (0.92).

Simulated stem weight was overestimated during the first 50 days, but showed a close relationship with observed data during the final 20 days of the experiment (Figure 4.5). The simulated values also showed a clear response to the second fertilizer application, while the observed data reflected a constant growth.

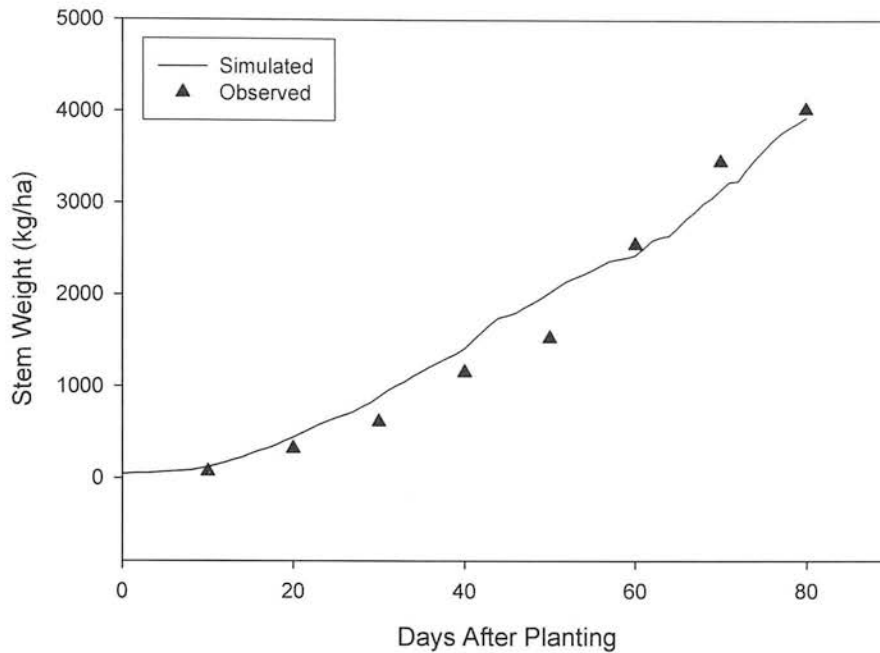


Figure 4.5. Simulated (line) and observed (point) data for stem weight for Napier grass harvested at 10-days cutting interval.

The performance of stem growth could explain why Napier grass continues to show an increase in plant height and biomass over time. However, as the plant continues to grow the quality of the biomass decreases, causing a decrease in nutritional value of the forage. The stem biomass over-prediction was not significant and therefore the value for RMSE (20%) was good, while the Index of Agreement was high (0.99).

4.6.3 Leaf number per stem

The leaf number per stem showed a very good fit between observed and simulated data. Both observed and simulated data showed a linear development. However, the under-prediction during the initial phase is caused by crop management characteristics and the structure of the CROPGRO model. CROPGRO mainly considers seed germination and emergence, although it can also handle transplants. Napier grass reproduction is by vegetative material and the initial number of leaves is the result of the transplant effect. The process for leaf growth is faster than

germination. The simulation of early growth and development needs to be re-evaluated during further development of the model. The predicted values maintained a constant growth rate, while the observed data showed some variation between sampling periods. This variation could be due to the variability in the plots that were sampled, which caused variation in soil moisture and nitrogen availability toward the end of the experimental period. The RMSE was good (15%) and the index of agreement was high (0.95), indicating a good prediction by the model.

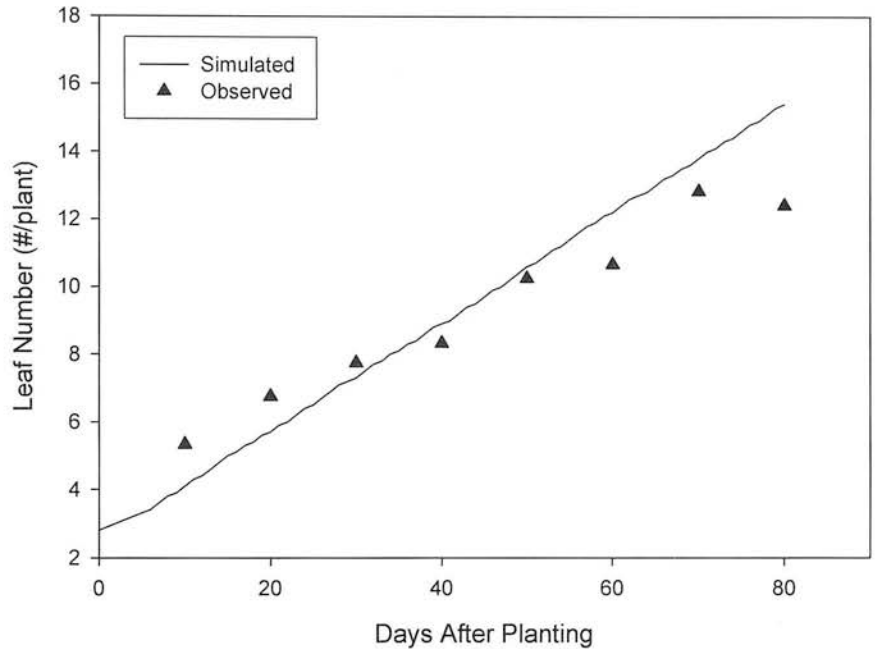


Figure 4.6. Simulated (line) and observed (point) data for leaf number per stem for Napier grass harvested at 10-days cutting interval.

4.6.4 Plant height

Plant height showed the best relation between simulated and observed data, when compared to the other variables. The canopy height coefficients were calibrated, starting with the values for *Brachiaria* and complemented with the experimental data from Napier. Both the observed and simulated data indicated a constant plant growth and increase in plant height, reflecting normal performance of Napier grass. Due to its indeterminate nature it continues to grow in height. In some cases a plant height of up to 4 m at an age of 250 days has been found (Woodard and Prine, 1993). The

value for RMSE was excellent (5%) and the Index of Agreement was the highest (0.99), showing an excellent agreement between observed and predicted plant height (Figure 4.7).

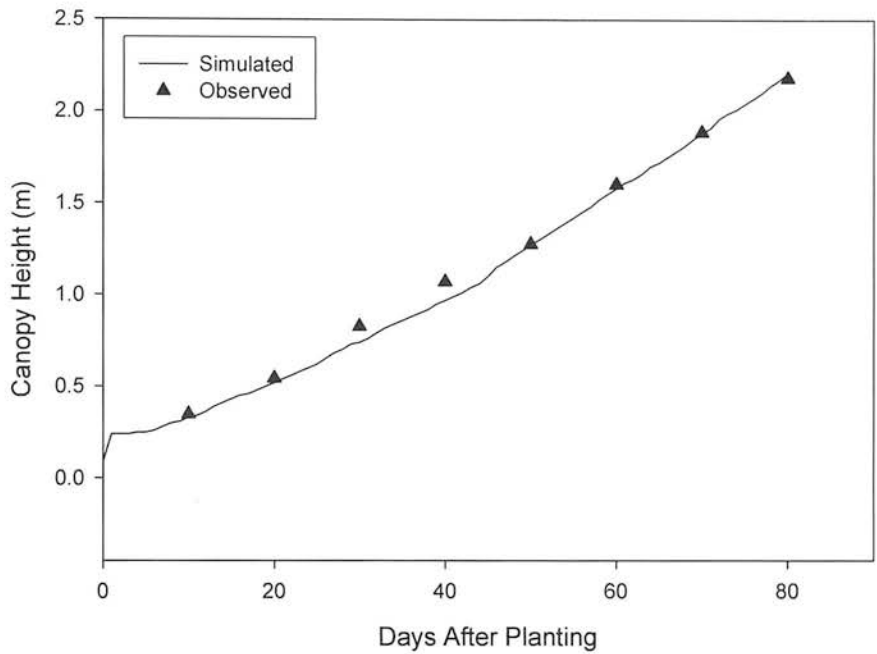


Figure 4.7. Simulated and observed data for plant (canopy) height in Napier grass harvested at 10-days cutting interval.

4.6.5 Leaf and stem nitrogen concentration (%)

Nitrogen concentration in the leaves and stem showed a strong relation between simulated and observed data, starting at the 30-days sampling. At 60-days, the simulated nitrogen concentration increased significantly, corresponding to the second N application, while the observed nitrogen concentration in the leaves increased slightly due to the N applied at 60-days (Figure 4.8). The performance of Napier grass found in this experiment is similar to the results of the experiment discussed in Chapter 3. There, Napier grass did not show a response to N fertilizer for the 30-days cutting interval, but the crop response to N fertilizer was very clear for the 60-days cutting interval. It, therefore, appears that the growth dynamics of Napier grass are slower during the first 4 to 6 week of regrowth and faster after that age. The RMSE

for the nitrogen concentration in leaves and stems was poor (over 40%). The Index of Agreement for both variables was 0.52.

Generally a higher N concentration in the leaves is correlated with a higher photosynthetic capacity. However, C4 grasses have low concentrations of N in the leaves, yet maintain a high photosynthetic rate (Rymph and Boote, 2002). This is consistent with the observations for Napier grass in this experiment, which showed that nitrogen concentration of the leaves and stems decreased starting at the third sampling, 30 days after the start of the experiment, while the plant increased its daily growth over 32%.

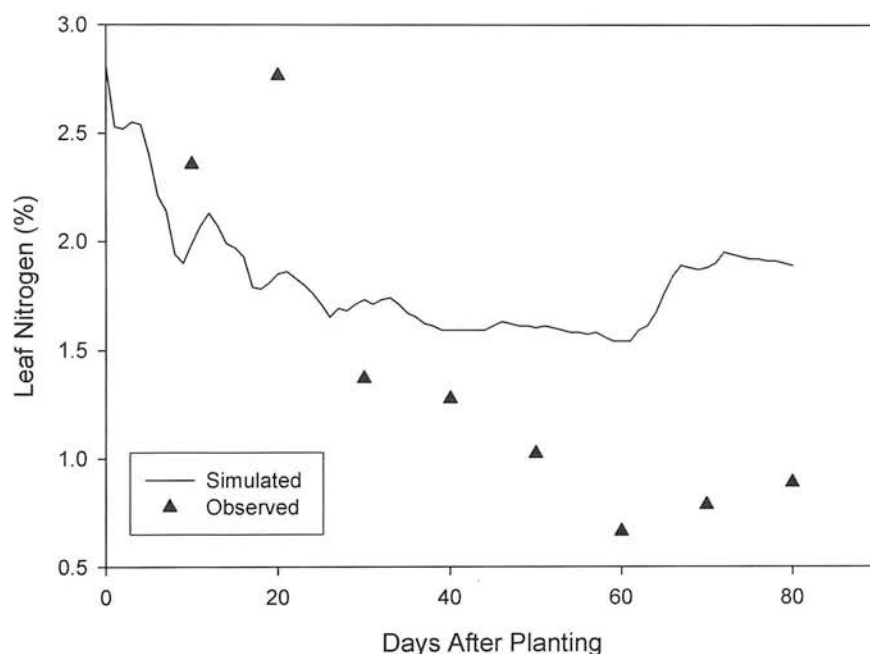


Figure 4.8. Simulated and observed data for leaf nitrogen concentration in Napier grass harvested at 10-days cutting interval.

4.7 Sensitivity analysis results

The sensitivity of the model to temperature and nitrogen fertilization was analysed for aboveground biomass, leaf and stem weight, leaf number per stem, plant height and the nitrogen concentration of leaves and stems.

Table 4.2. The impact of changes in temperature on Napier grass growth and development

VARIABLES	Control*	+ 1°C	+ 2°C	+ 3°C	- 1°C	- 2°C	- 3°C
Biomass (kg DM ha ⁻¹)	8284	8210	8156	8130	8147	8045	7945
Leaf number per stem	15.6	15.6	15.6	15.6	15.8	16.1	16.3
Plant height (m)	2.31	2.32	2.33	2.32	2.39	2.47	2.54

*|Result of Model with the highest N application at 80-days, with adjusted real mean temperature.

For aboveground biomass, the highest cumulative forage yield predicted by the model was 8284 kg DM ha⁻¹ at 80 days at the end of the experimental period. This result indicates the maximum crop production for these experimental conditions with the highest nitrogen fertilizer rate used (500 kg N ha⁻¹ year⁻¹). This result is the reference data (Control) to compare changes in biomass production as effected by the temperature increase or decrease that was used for the sensitivity analysis (Table 4.1). The model responded to the temperature changes and showed a systematic decrease in forage yield at 80-days of pasture age. Aboveground biomass showed a reduction in biomass production for every degree increase in temperature. So, for +1, +2 and +3°C temperature increase, biomass production decreased by 0.4, 1.0 and 1.4%, respectively. For a temperature decrease of -1, -2 and -3°C, aboveground biomass decreased in 1.2; 2.4, and 3.6%, respectively (Table 4.1). Leaf number only showed a positive response to a reduction in temperature for -1, -2, and -3°C. The number of leaves on the main stem increase by 1.3, 3.2 and 4.5%, respectively (Table 1). The increase in temperature had only a slight influence on plant height. However, the decrease in temperature by -1; -2, and -3°C showed an increase in plant height of respectively 3.5; 6.9 and 10%.

A sensitivity analysis for nitrogen fertilizer application rates included the three established treatments, two intermediate applications and one higher rate of N than the maximum that was applied in the experiment (Table 4.2). The sensitivity analysis based on the non-fertilized treatment (Control) indicated that for every 125 kg of N applied, biomass increased, but that pasture growth was not proportional to the increase in N fertilizer. With the lowest amount of fertilizer (125 kg N ha⁻¹ year⁻¹),

biomass production increased in the order of 41% over the Control, but as the N application were increasing with the other higher treatments, the proportional difference respect the Control were decreasing under 41%. (Table 4.2).

Table 4.3. The impact of nitrogen fertilizer on Napier grass growth and development

VARIABLES	Nitrogen Fertilizer					
	<u>0 kg N</u>	<u>125 kg N</u>	<u>250 kg N</u>	<u>375 kg N</u>	<u>500 kg N</u>	<u>625 kg N</u>
Biomass (kg DM ha ⁻¹)	3535	5969	7452	7983	8284	8615
Leaf number per stem	15.5	15.5	15.6	15.5	15.6	16.6
Plant height (m)	1.84	1.88	2.01	2.15	2.31	2.42

The nitrogen fertilizer sensitivity analysis did not detect any differences in the total number of leaves per stem (Table 4.2). However, for plant height, the Napier grass model responded to all fertilizer treatments and showed a positive response to the increase in nitrogen (Table 4.2).

4.8 Conclusion

This study showed that the CSM-CROPGRO model can be used as template for the development of a dynamic crop simulation model for Napier grass. The new CSM-CROPGRO-Napier model was able to predict the performance of this pasture based on local weather and soil data and crop management fairly accurate.

It is expected that the application of the Napier grass model can have a high impact on potential milk production and the long-term sustainability of dairy systems, not only for smallholder farmers in Bolivia, but also in other developing countries, where milk production is the main source of family income and forage is the main feed for dairy cattle. However, it will be necessary to refine and improve several details associated with biomass and nitrogen prediction. Furthermore, for the model to be used and adapted widely, it will also need to be able to respond properly to applications of organic fertilizers that are commonly used in these smallholder farmer systems, including the return of manure of dairy cattle back to the field. After further evaluation of the model, it will be possible to determine the optimum

management scenarios for Napier grass and to predict the quantity and structural quality of plant material, including the leaf – stem ratio and nitrogen concentrations of the individual plant components and to evaluate the long-term sustainability of Napier grass pasture.

Abstract

Napier grass (*Pennisetum purpureum*, Schum.) is a forage resource that is used widely in tropical and subtropical regions. The main characteristic of Napier grass is its capacity to produce a large amount of aboveground biomass. In cut and carry systems that are common in tropical farming systems around 90% of the plant is harvested for feeding animals. Its high potential to produce biomass is one of the main justifications for the development of a computer model that can simulate Napier grass growth and performance for different soil and weather conditions and management scenarios. The Cropping System Model (CSM)-CROPGRO was adapted for Napier grass and incorporated into the Decision Support System for Agrotechnology Transfer (DSSAT) program. This chapter evaluates the performance of the model regarding phenology, crop growth and development, and nitrogen fertilizer applications. The experimental data set that was discussed and analysed in Chapter 3 was used for model evaluation. At difference in these data the cutting intervals applied were at 30 and 60-days, meaning sampling repetitions in the same plant according cutting interval along the 240 days of evaluation. The best response for model evaluation was obtained for biomass weight not only for the 30-days cutting interval, but also for the 60-days cutting interval. These results are satisfactory, considering that biomass production is the most important variable for cut and carry forages. However, some differences were observed in the prediction of biomass for the last two sampling periods. The explanation for these differences is that Napier grass was assessed at two physiology stages under repeated measurement with seasonal variations along the experimental period.

5.1 Introduction

The evolution of agricultural technology has demonstrated that computer simulation models can be important decision support tools, not only to assist in research understanding, but also to achieve a sustainable land management (Boote *et al.*, 1996; Hoogenboom, 1996; Tsuji *et al.*, 1998; Cheeroo-Nayamuth *et al.*, 2000; Bowen *et al.*, 2003). Napier grass (*Pennisetum purpureum* Schum.) is a tropical pasture with a high capacity to produce forage. However, in order to be able to express these characteristics, the crop requires an optimum environment for water, temperature and nutrients. In the majority of tropical and subtropical countries, Napier grass is used through a cutting system, providing the entire plant as forage to animals. This type of production system requires specific crop management to control both the quantity and quality of the forage. Nitrogen that is available in the soil or provided through fertilizer and the physiological stage at which the crop is cut both have an impact on the protein content of forage biomass. Furthermore, soil moisture and temperature have a strong influence on biomass production. For example, for the cutting intervals of 30 and 60-days, it was found that the amount of Napier grass that was harvested varied by 296 kg DM ha⁻¹ for each 1°C change in temperature (Joaquin *et al.* 2004). For smallholder dairy systems, Napier grass is one of the most important resources that can be used for livestock intensification to produce a high quantity of forage on small amount of land. However, there is a need to complement this with a decision support tool to control the relation among environmental conditions and crop management and to help optimize forage production, including both forage quality and quantity.

The generic legume model CSM-CROPGRO was originally developed for soybean, peanut and common bean (Hoogenboom *et al.*, 1992; Boote *et al.*, 1998; Jones *et al.*, 2003). However, the model has been adapted for other species, including chickpea, velvet bean and tomato, by modifying the crop species parameters and functions and by obtaining new cultivars coefficients (Singh and Virmani, 1994; Scholberg *et al.*, 1997; Giraldo *et al.*, 1998; Hoogenboom *et al.*, 2003; Hartkamp *et al.*, 2002). The CSM-CROPGRO model that is part of the Decision Support System

for Agrotechnology Transfer (DSSAT) Version 4.0 (Jones *et al.* 2003; Hoogenboom *et al.*, 2004) was used to develop the structure of the Napier grass model. The genotype files, including the species, cultivar and ecotype files of the Brachiaria (*Brachiaria decumbens*) and Bahia grass (*Paspalum notatum*) models were used as a template.

The objective of the present study was to evaluate the performance of the CSM-CROPGRO-Napier grass model to different cutting intervals and nitrogen fertilizer applications.

5.2 Materials and methods

The experimental data that were used for model evaluation were described in detail in Chapter 3. However, in this chapter a more-detailed description is presented due to the input requirements for the CSM-CROPGRO-Napier model, including a description of the soil profile. The physical and chemical characteristics of the individual soil layers up to a depth of 100 cm were determined prior to the start of the experiment. The soil texture of the top layers was clay loam. The nitrogen concentration was 0.16 %, pH (H₂O) was 6.3, soil organic carbon was 1.01 %, and the bulk density was 1.58 g/cm³. The crop was planted (vegetative material) 90 days prior to the start of data collection and the plant density was one plant per m². Two stems composed of three nodes each were planted to obtain each plant. There were three treatments of inorganic fertilizer that included a Control (0), 250 and 500 kg N ha⁻¹year⁻¹. Each treatment with fertilization was divided and applied according the two cutting frequencies (30 and 60-days). The experiment was a split plot design with three replicates for each treatment. During the experiment, nitrogen fertilizer was applied after each cut or forage harvest. So, for the cutting interval of 30-days, nitrogen was applied at a rate of 20.8 and 41.5 kg N ha⁻¹ for the treatments of 250 and 500 kg N ha⁻¹year⁻¹, respectively, after each harvest. For the 60-days cutting interval this corresponded to a nitrogen application of 41.5 and 83 kg N ha⁻¹ per application after each harvest. The evaluation period was 240 days, meaning eight sampling period for the 30-days cutting interval and four sampling period for the 60-days cutting interval. Daily weather data, including temperature, solar radiation and

rainfall were obtained from a meteorological station located at approximately 0.5 km from the experimental site. The average maximum and minimum temperatures were 30.4°C and 18.4°C, with extremes of 37 and 7°C, respectively. Total precipitation was 424 mm. Due to insufficient rainfall seven irrigations at a rate of 50 mm per application were applied for each treatment.

The CSM-CROPGRO-Napier grass model, as discussed in Chapter 4, was developed with the experimental data set described there. While, for the model evaluation, data set correspond at the grass was cut at intervals of 30 and 60-days, meaning that during the experimental period the same individual plants were sampled eight times for the 30-days and four times for the 60-days cutting interval.

The current experimental period included four seasons, e.g, from January to October, which means that Napier grass was affected by different temperatures and that the variations in soil moisture were representative for each season. In farmer's systems, this seasonal effect impacts the decision for either a shorter or longer cutting interval and, therefore, biomass production is variable according to the requirement of the cattle that are being fed.

For model evaluation the appropriate soil, weather and experimental detail files were created, as described in Hoogenboom *et al.* (2004).

5.3 Results and discussion

For the evaluation of the Napier grass model the simulated data were compared with the observed data and an error analysis was applied, including the root mean square error (RMSE) and the Index of Agreement. The observed data that were included in the model evaluation analysis were biomass production, plant height, number of leaves per stem and nitrogen concentration in plant. For model evaluation, data were analysed for only one N fertilizer treatment to facilitate the comparative analysis for simulated and observed data, considering that the purpose of this analysis was the model's response to real weather and soil conditions and management practices.

5.3.1 Aboveground biomass

Simulated total aboveground biomass for the 30-days cutting interval was similar to the observed aboveground biomass for the entire 240 days evaluation period except for the final harvest (Figure 5.1). In general, aboveground biomass had a fairly good prediction, as shown by the RMSE of 19 %, but the index of agreement was poor, i.e. 0.34. For the 60-days cutting interval, simulated aboveground biomass was very similar for the first two harvests, but decreased significantly for the third and fourth harvest dates (Figure 5.2). The RMSE was fair, i.e., 24% and the Index of Agreement low, i.e., 0.25.

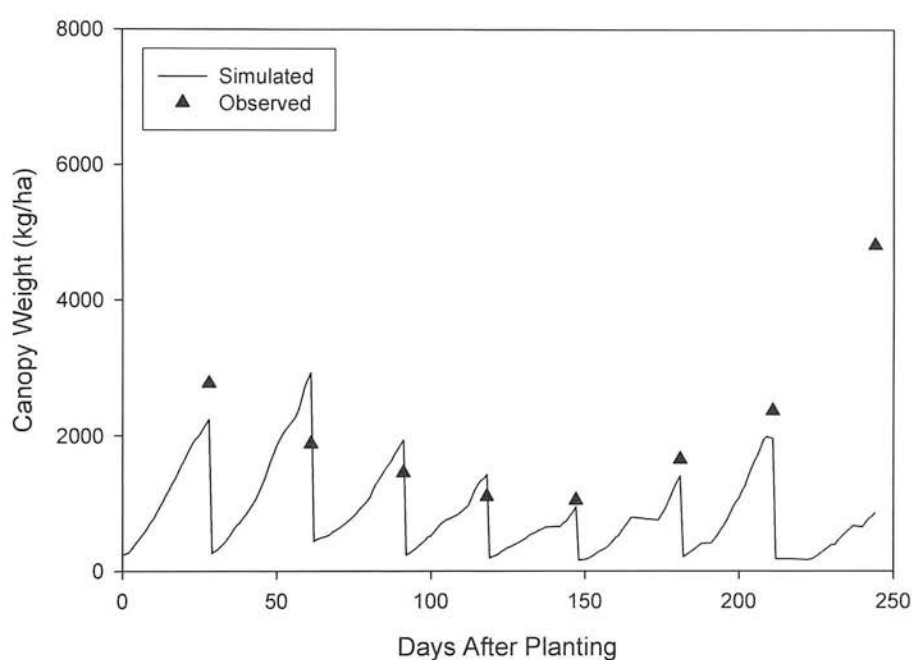


Figure 5.1. Observed (points) and simulated (line) data for aboveground biomass for Napier grass for the 30-days cutting interval.

For Napier grass, total biomass is the most important variable and the model showed a very good prediction for most of the sampling period for the 30-days cutting interval (Figure 5.1). In the case of 60-days, prediction was good for the first two sampling times only (Figure 5.2). The distinct differences at the end of the sampling period could be explained by a strong temperature increase in August and

irrigation that was applied (Figure 3.1) to which the crop model did not respond. In addition, the crop model only predicts total green biomass, while the Napier grass that was harvested included a mixture of green, senesced and dead biomass, as discussed in Chapter 4. Overall the model was evaluated for four different seasons. In general the model seemed to perform better during Fall and Winter seasons and in predicting growth of young Napier grass plants compared to older and established Napier grass plants.

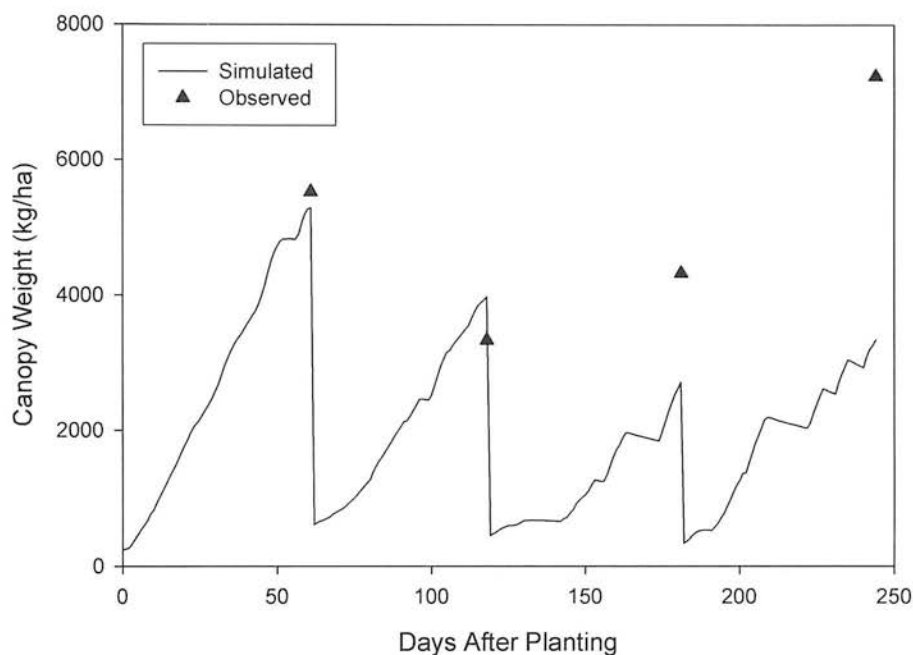


Figure 5.2. Observed (points) and simulated (line) data for aboveground biomass in Napier grass for the 60-days cutting interval.

5.3.2 Leaf number per stem

The number of leaves per stem was under-predicted for the 30-days cutting interval for all growth analysis samples (Figure 5.3.). The RMSE was intermediate, i.e., 26% and the Index of Agreement was low, i.e., 0.25. However, for the 60-days cutting interval the simulated and observed leaf number per stem were very similar for the 1st and 2nd harvest, but decreased considerably for the 3rd and 4th harvest (Figure 5.4). The large difference for the final two sampling periods resulted in a rather high RMSE, i.e., 41%, and a small Index of Agreement, i.e., 0.34. Similar to biomass

prediction, the model had some difficulties with predicting leaf number per stem for the second part of sampling period, where the growth and development dynamics of the plant were reactivated by an increase in temperature.

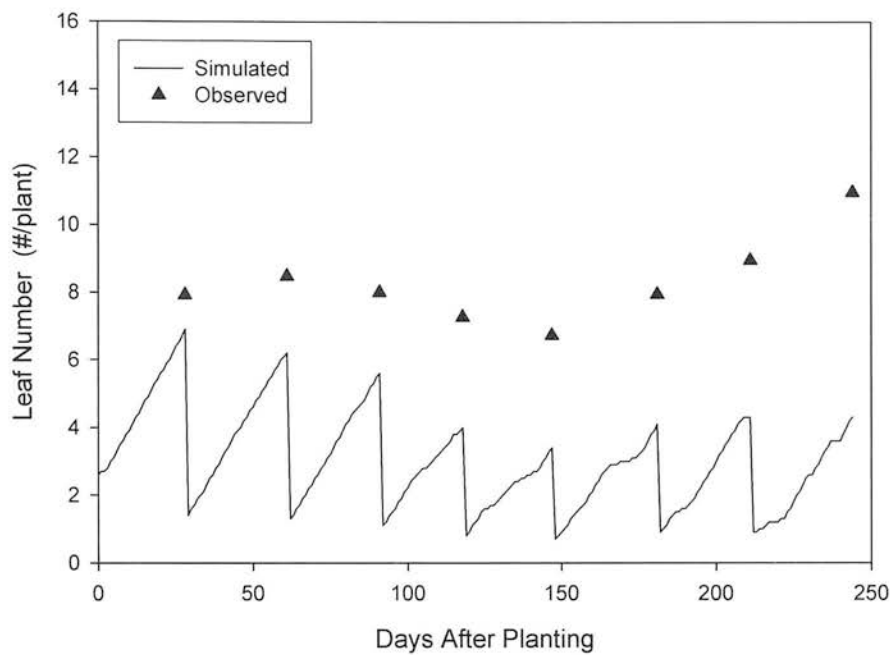


Figure 5.3. Observed (point) and simulated (line) data for the number of leaves per stem for Napier grass for the 30-days cutting interval.

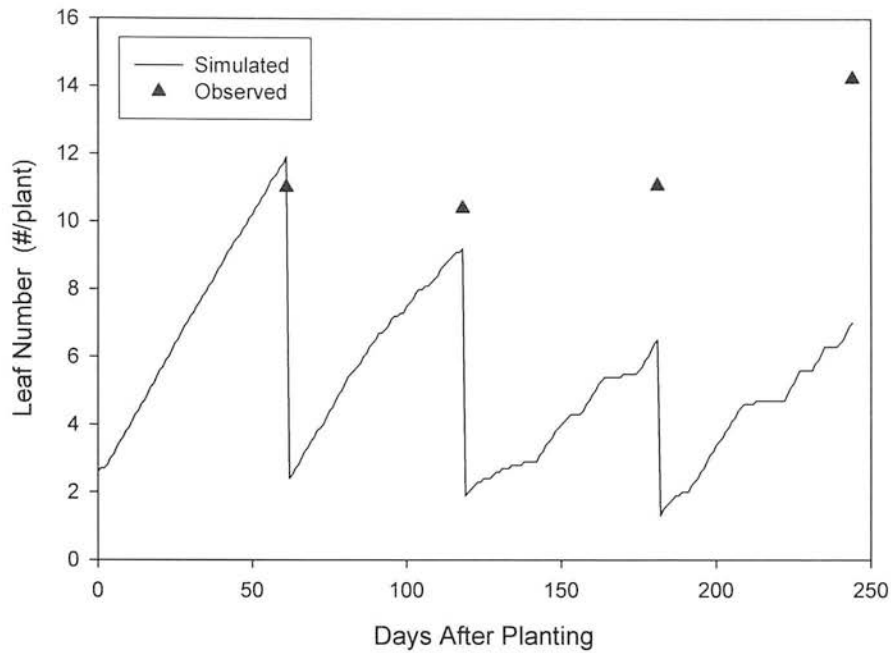


Figure 5.4. Observed (point) and simulated (line) data for the number of leaves per stem for Napier grass for the 60-days cutting interval.

5.3.3 Plant height

Plant height for the 30-days cutting interval showed the RMSE was less than 20%, which indicates a fairly good simulation. However, the relation between observed and simulated data as shown in Figure 5.5 does not show the harvest effect for every cut period. Plant height for the 60-days interval was predicted very well, with a minimum RMSE of 1 % (Figure 5.6). The Index of Agreement for the 30-days cutting interval was 0.34 and for the 60-days cutting interval was 0.45.

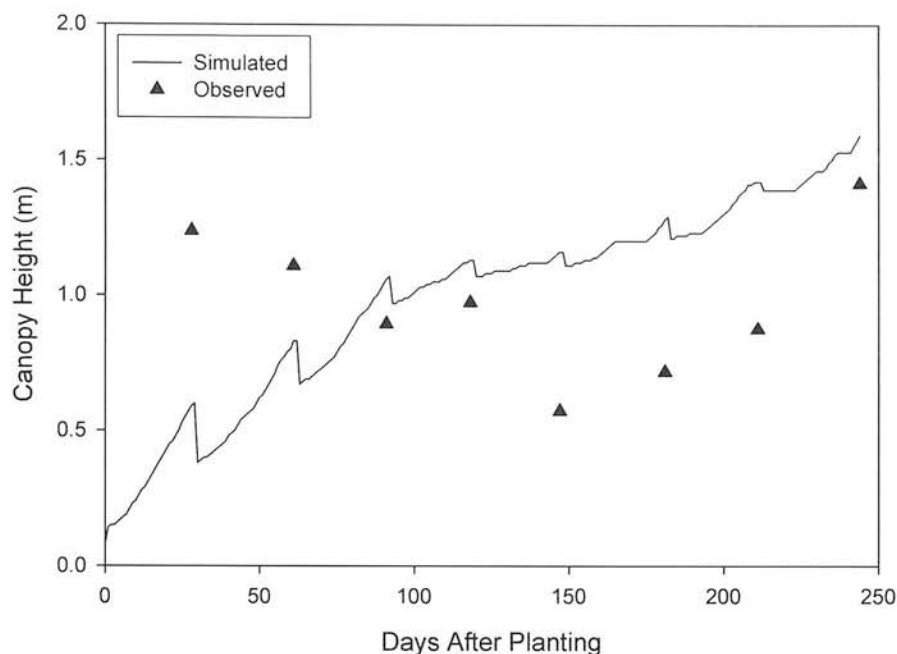


Figure 5.5. Observed (point) and simulated (line) data for plant height (m) for Napier grass for the 30-days cutting interval.

Was demonstrated that the model has the capability not only to predict biomass production but also some plant structural characteristics. It is important to state that for evaluation of crop performance with the model, different management practices were applied in this experiment when compared to the experimental data that were used for model calibration. One other issue in the adaptation of CSM-CROPGRO for Napier grass relates to crop management. As shown in this experiment, Napier grass is cut frequently, as often as once every 30 days, while traditional row crops are harvested once at physiological and harvest maturity. This affects, for instance, how canopy height and vegetative growth stages are simulated as discussed in the previous section. During each cut they are reduced back to a few growing points and to the height at which the crop was cut. This can be clearly seen in Figure 5.6 where plant height is not adequately reduced, especially for the final three harvests, although there is a good agreement between simulated and observed canopy height.

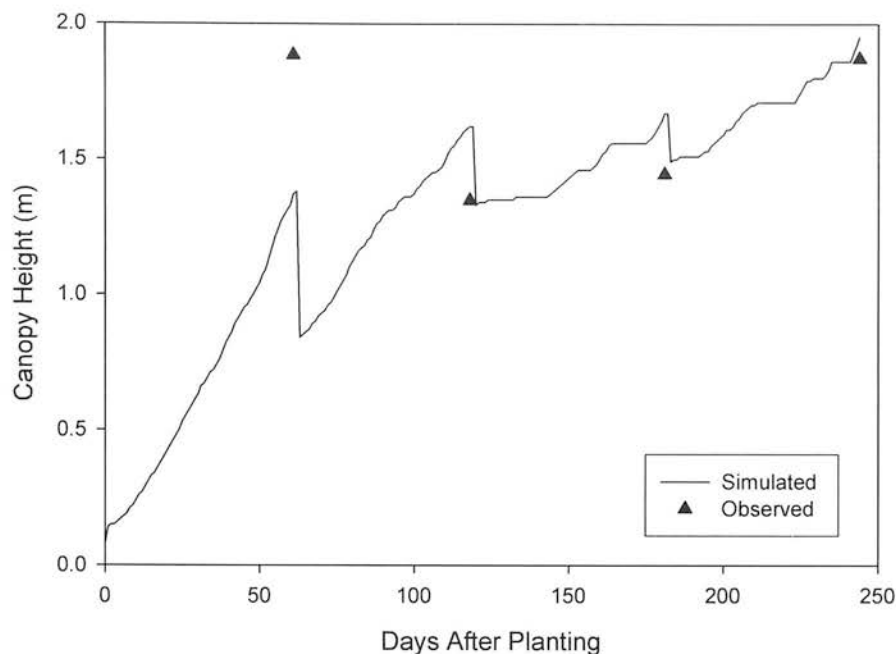


Figure 5.6. Observed (point) and simulated (line) data for plant height for Napier grass for the 60-days cutting interval.

5.3.4 Nitrogen concentration

The model evaluation for N concentration in leaf and stem for both cutting intervals showed very close prediction at the cut moment (Figures 5.7 and 5.8). Although RMSE and Index of Agreement were poor (over 50% and under 0.2, respectively) the values for simulated and observed at each harvest were very similar compared to the predicted increase when fertilizer was applied. These results are much better than those presented for the adaptation of the CSM-CROPGRO model for *Brachiaria* (Giraldo *et al.*, 1998).

The prediction of the nitrogen concentration in leaves, stems and total aboveground biomass is different from a forage grass when compared to an annual crop. For an annual crop the physiological processes terminate when physiological and harvest maturity are predicted, while for a forage grass the nitrogen concentration might decrease at the time when the cut takes place, but then increases significantly with new growth and supplemental fertilizer after harvest. This will require somewhat different nitrogen dynamics, although the model showed a very

strong response to the nitrogen fertilizer application after each cut (Figures 5.7 and 5.8).

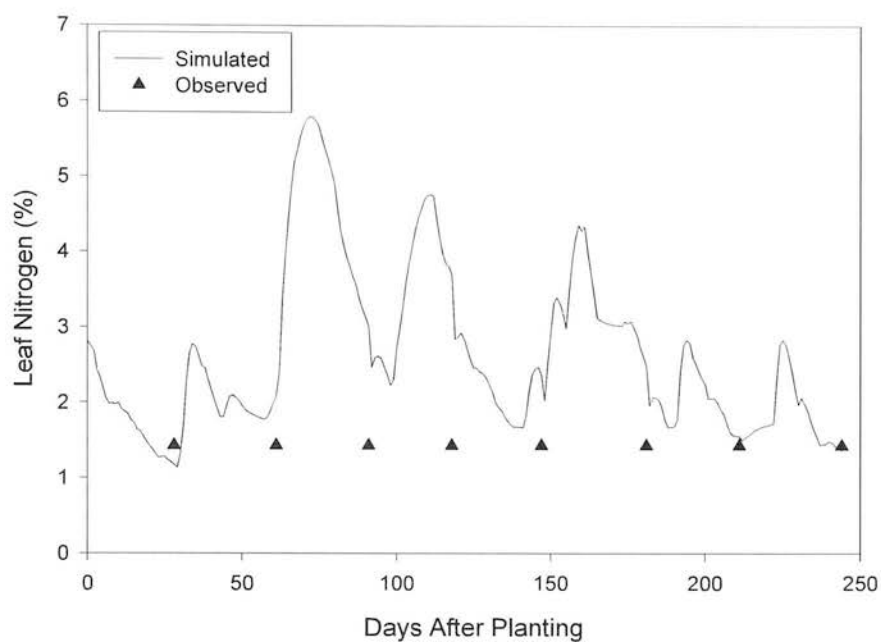


Figure 5.7. Observed (points) and simulated (line) data for nitrogen concentration in leaves for Napier grass for 30-days cutting interval.

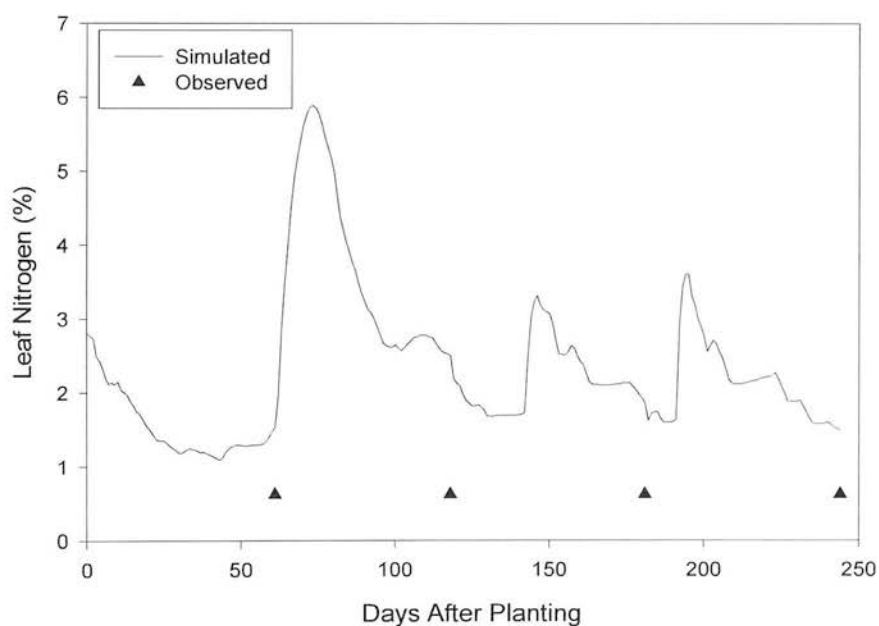


Figure 5.8. Observed (points) and simulated (line) data for nitrogen concentration in leaves for Napier grass for the 60-days cutting interval.

5.4 Conclusion

The Napier grass model was evaluated for the tropical climatic conditions of Santa Cruz, Bolivia. The experimental data that were used for model evaluation included two different crop management strategies related to nitrogen fertilizer application rates and cutting intervals.

In general, the model showed a fairly good prediction for aboveground biomass, leaf and stem biomass and plant height. The model simulated the plant nitrogen balance fairly well and showed a strong response of leaf and stem nitrogen concentrations to the applications of nitrogen fertilizer following each cut.

The results from this evaluation study indicate that the CSM-CROPGRO-Napier grass model has the potential for application as a research and technology transfer tool for sustainable management of Napier grass under tropical and subtropical conditions. However, it will be necessary to continue to adjust the model to deal with some of the differences between annual crops and forage crops, including multiple harvests.

6.1 Introduction

This chapter integrates the results of the different experimental studies that were conducted and the Napier grass model that was developed in order to attain a general understanding of the growth and developmental dynamics of Napier grass and its response to environmental conditions and crop management. Furthermore, this chapter proposes how this model can potentially be used in decision support to help resource-poor farmers. The resulting model will further allow the identification of the environments, soil nitrogen and management options that are capable of producing changes in the state of the sward and its associated productivity. Through each experiment, the grass is characterised by unique responses to the environment, fertilizer and pasture management, and this will be reflected in different contributions to the aboveground biomass production, stem population and other structural variables. Based on the results of the experiments that were conducted, Chapter 4 describes a crop simulated model based on the CROPGRO model template, which structure is supported by weather data, soil and plant physiology. Finally, the advantages and limitations concerning the methodology and applicability of this study are discussed, and solutions and recommendations to overcome some of the problems are provided.

6.2 Using manure for fertilizing Napier grass

The main goal of this experiment was to define a production scheme for smallholder dairy systems. The proposed technology is based in the resources that a smallholder farmer has available, including cattle, manure and Napier grass, and the limitations to produce adequate forage resources to cover the requirements of the animals. One factor was to determine the nitrogen uptake by grass and nitrogen return through recycling of cows manure. However, it was necessary to consider the amount of land used for producing Napier grass and the farm's capacity to accumulate manure, which will depend on cattle population in this analysis. The

experimental procedures were designed to include manure application practices that had the potential to be adopted by farmers. The biomass production of Napier grass as affected by manure fertilization responded proportionally to the quantity of manure that was applied. The cutting interval of 60-days resulted in a higher forage yield than the 30 and 45-days cutting intervals and the difference resulted from the more efficient photosynthesis with longer cutting intervals.

Cattle play an important role in the rural economy and in soil fertility management when the manure is recycled and used as an organic fertilizer for the crop. In general, ruminant are the most important and widespread source of manure, especially in smallholder systems (Hilhorst *et al.*, 2000). However, in the tropical agricultural systems of Bolivia the full potential of manure as resource has not been reached, because, due to the lack of farmers' knowledge about the benefit of manure applications to increase and intensify the production of forage in small areas.

The storage method impacts the rate of nitrogen loss during decomposition. For instance, Lekasi *et al.* (2001) found a range of 2.0% and 30.1% of nitrogen losses during the composting phase. Beauchamp (1986) stated that rainfall dilutes the total ammonia in manure, and thus reduces the available ammonia after application. However, in the present study we did not find a significant variation in N among fresh and stored manure. We attributed this small difference due to the crust that formed quickly over the manure exposed to the environment. This crust protected it from the detrimental effects of sun and rainfall and provided anaerobic conditions for manure decomposition.

Analysing biomass production of Napier grass and protein concentration, we consider that to achieve an annual equilibrium of N in the soil, the amount of manure required to compensate for the extracted nitrogen should be 30 t of DM manure per hectare. It is important to note that the experiment was conducted during the rainy season, i.e., during summer and autumn, which is the period of highest biomass production. It might, therefore, be possible that the remaining N in the residual manure at the end of the experimental period would be adequate to cover the requirements for two additional cuts or harvests when the Napier grass biomass production is lower, before a new application of manure is made.

The N balance analysis showed that the equilibrium between total N applied and N extracted was obtained for the treatment in which 30 t ha⁻¹ of manure was applied and with a cutting interval of 60-days. The treatment with 60 t ha⁻¹ of manure application also had a positive N balance for all cutting interval. The N extracted and the N balance, clearly explain why Napier grass without fertilization decrease its biomass production and deflect de soil fertility in short time.

An important consideration is the labour requirement for the manure management in smallholder dairy systems. The target is to promote the fact that this resource is very useful as fertilizer and its only cost is labour. One way to reduce the labour for manure storage and distribution is to grow Napier grass near the stake where the animals are kept. This practice reduces the labour requirement for carrying on both management practices, i.e. manure application and grass harvests and associated transportation.

In summary, the use of manure to fertilize Napier grass in dairy systems is a viable practice to improve biomass production and to maintain soil fertility. Furthermore, this study showed that farmers can accumulate 30 t ha⁻¹ year⁻¹ of manure to apply along the year. The manure recycling practice will result in approximately 350 kg of additional DM of forage per ton of applied manure.

6.3 Analysing the interaction between temperature and inorganic nitrogen fertilization

This study showed that the temperature difference between the hottest and the coldest months affects the performance of Napier grass. Many studies have demonstrated that for tropical environments, C₄ grasses have an optimum temperature for growth and development. When the temperature decreases to 20°C, it affects the rate of grass growth in general (Ferraris *et al.*, 1986; Sweeney and Hopkinson, 1975; Ivory and Whiteman, 1978; Ludlow and Wilson, 1971). There was especially a dynamic response for the numbers of stems per plant for instance when the temperature decreased the stem number increased. For many tropical grasses the optimum temperature for tillering is similar to the optimum temperature for growth

(Jozwik, 1970; Wilson & Ford, 1971). However, in this experiment, the relation between biomass production and the number of stems per plant was negative. This mean that a higher stem population do not mean higher biomass production. A tillering response to the cold season through an increase in the number of stems was also found for Rhodes and Kikuyu grasses by Ivory and Whiteman (1978), but under controlled environmental conditions. Ferraris and Sinclair (1980) found a similar tendency for a Napier grass pasture. However, the increased number of stems does not necessarily result in an increase in biomass production in Napier grass and the response is similar to the response of other temperate species (Langer, 1963).

The measurement of plant height as a function of cutting frequency allowed us to determine the rate of plant elongation, which reflects the plant's vertical response to the environmental conditions, e.g., soil and climate. Ferraris *et al.* (1986) stated that a low in plant height was the initial phase of slow elongation lasting approximately four weeks, followed by rapid elongation. However, in the present experiment, the 30-days cutting interval had a greater elongation rate than the 60-days cutting interval. So, there was no relation with biomass production, because the growth rate for the 60-days cutting interval was higher than for the 30-days cutting interval (Table 3.1). For Napier grass, Ferraris *et al.* (1986) found that the elongation rate reached a maximum of 2.9 cm day⁻¹ between 27/22°C and 33/28°C of day/night temperature, and a minimum of 1.7 cm day⁻¹ when the day/night temperature decreased to 21/16°C. These values are in agreement with the values determined in the present experiment (Table 3.3). However, these values are higher than the results reported by Muia *et al.* (1999), who determined maximum and minimum plant elongation values of 1.64 and 0.91 cm day⁻¹, respectively. These similarities and differences are due to weather and soil conditions, as Napier grass showed that it is a species that is sensitive to temperature changes and N availability. Cruz and Boval (2000) found that the internode length is mainly responsible for differences in elongation rate and that it might increase with greater nitrogen availability. This concept has relation with the results obtained in the present experiment the elongation rate was higher as higher were the N dose fertilizer for all treatments (Table 3.3).

The length of each individual leaf length is a function of species and variety and plant growth dynamics, where the time to reach maximum leaf size is a function of the rate leaf elongation. Leaf length also varies between the position of the leaves on the plant and final leaf size is mainly affected by the amount of resources available to the plant, especially nitrogen and soil moisture as well as temperature (Gastal and Durand, 2000; Lemaire and Agnusdei, 2000). In the present experiment, Napier grass responded to both temperature and N fertilization, and the mean leaf size in the 60-days cutting interval with the highest N level was 9.4% longer than the control treatment. However, this difference did not affect the leaf-stem ratio; the control treatment had the highest proportion of leaves.

A detailed correlation analysis showed that for Napier grass, plant height was correlated to total DM per hectare (0.73). This provides a practical application for the farmer, who can use plant height as a tool to calculate instantaneous biomass per unit land area and consider the forage requirement for cattle.

The nitrogen use efficiency (NUE) analysis identified the relation between N applied and N uptake by the plant uptake. This analysis shows the biological viability to use N inorganic fertilizer, considering the grass response respect and the nitrogen price. In some cases, land use and the age of the pasture can have a positive impact on NUE. For instance, Gargano *et al.* (2001) found a NUE for *Digitaria eriantha* established four years earlier that was 30% higher than the NUE of this Napier grass experiment.

The nitrogen recovery efficiency (NRE) showed poor values for the 30-days cutting interval, which indicated an inadequate time to recover the N that was part of the N fertilizer. However, the 60-days cutting interval showed a similar response for both N fertilizer treatments (250 and 500 kg N ha⁻¹year⁻¹). This indicates that both NRE and NUE depend more on the cutting interval than the amount of N fertilizer that was applied.

The gross nitrogen losses (GNL) based on the equation proposed by IFA/FAO (2001) indicated a slightly proportional variation among treatments, as the GNL depends of the amount of fertilizer applied. So, GNL depends of the amount of N

application only. When the amount of N is greater, the GNL increases proportionally, independently of the application frequency.

In summary this study of N balance analysis showed that the maximum amount of N that was applied ($500 \text{ kg N ha}^{-1} \text{ year}^{-1}$) covered 65% of the N uptake by the pasture, meaning that the N applied was not enough to cover the N requirement of the plant and that additional N from the soil was used.

6.4 Development of a dynamic simulation model for Napier grass

The adaptation of the CROPGRO model for Napier grass was a somewhat complicated process, mainly due to the original application of the CROPGRO model for annual crops and growth and development of Napier grass, which is a perennial crop. In addition to the duration of the growing season, there are also differences in harvest, as the annual crop is only harvested once, while a forage grass can be cut or grazed many times during the growing season. Furthermore, there was a need to conduct a special experiment to support the development of the model. In addition, literature references from Napier grass and other tropical grasses were used to obtain other parameters, coefficients and response functions. After the completion of the experiment and a comprehensive literature review, the model was developed as presented in detail in Chapter 4. For biomass production, the slight over-prediction by the model could be due to the natural high growth potential of Napier grass. It might also be possible that the growth of Napier grass in the experiment was not completely manifested due to limitations in available nitrogen and especially water as most of the experimental period was conducted during the dry season and there were some problems with the irrigation system. In addition, Napier grass is a crop that shows a wide variation in its performance and response to local environmental conditions and crop management. For instance, the literature review showed that the values for production of biomass ranged from 10 to 40 t per hectare per year (Wouters, 1987; Skerman and Cameron, 1990; Schreuder *et al.* 1993; Boonman, 1993; Anindo and Potter, 1994; Humphreys, 1994).

Leaf weight was overestimated from 10 to 60 days after the start of the experiment and it affected the over-prediction of total biomass. However, from 70 to 80 days after the start of the experiment, the simulated values only included the predicted green leaf weight, while, while the observed data included both dead and green leaf weight (Figure 4.4). This is partially due to the fact that CROPGRO is annual crop model that predicts senescence. Further modifications to the model might be required to deal with this issue.

Simulated stem weight was slightly over-estimated until 50 days after the start of the experiment, but was similar to observed stem for the remaining period up to 80 days after the start of the experiment (Figure 4.5). The model for stem showed an indeterminate growing rate and both the model and observed data showed this, which can explain why Napier grass continues to increase in height and biomass production for an indefinite time. Of course, as the plant continues to grow, the quality of the biomass decreases and is a loss -to the nutritional value of the forage.

There was a very good fit between observed and simulated leaf number per stem. Both observed and simulated leaf number showed a liner increase. However, there was an under-prediction at the start of the experiment, possibly due to the crop management characteristics and the structure of the CROPGRO model. The model considers either planted seed and emergence or transplants, while Napier grass reproduction is by vegetative material and the initial leaves number are the results of the plant regrowth, which process is faster than germination. To initialize the model we used the transplant option. As Napier grass is an indeterminate crop, leaf senescence is determined by the model, because, there is always leaf senescence, even in indeterminate crops. The predicted values maintained a constant growth rate, while observed data showed some variation between the individual sample periods. This variation is probably due to senescence, which was not measured, or by the variability in the plots that were sampled, due to some variation in soil moisture and nitrogen availability during the experimental period and the variation between plants.

Plant height showed the best relation between simulated and observed data, when compared to the other variables. Both the observed and simulated data indicated constant plant growth and reflected a normal performance of Napier grass when

grown under optimum conditions. Due to its indeterminate nature, Napier continues to increase in height unless it is cut as part of crop and harvest management. In some cases a plant height of up to four m has been measured for plants that are 250 days or older (Woodard and Prine, 1992). This particular characteristic of Napier grass when compared to annuals crop was very well simulated by the CROPGRO model and it responded very well with respect to predicting plant height.

There was a good correlation between the observed and simulated nitrogen concentration in the leaves and stems up to 30 days after the start of the experiment (third sampling). From 60-days, the simulated data increased significantly in response to the second N application, while there was only a slight increase in observed leaf N and a decrease in observed stem N. This crop performance has relation with the results obtained from the experiments discussed in Chapter 3. In this experiment Napier grass did not show a response to N fertilizer for any one variable at the 30-days cutting interval, but the crop response to N fertilizer was clear at the 60-days cutting interval. So, the observed data of Napier grass dynamic growth was slower during the first 4 to 6 week of regrowth and faster after this period.

The sensitivity analysis showed that the model responded to the effect of temperature and nitrogen fertilizer variation. The temperature sensitivity analysis, Napier showed a systematic biomass decrease for both higher and lesser temperature based in the maximum biomass value obtained in the observed data (Table 4.2). So, applying higher or lesser temperature value according FileX, biomass production tended to decrease, but the variation was not higher than 2% per every degree Celsius increased or decreased.

A sensitivity analysis for nNitrogen fertilizer was conducted, including two new inter-medium and a highest dose application becoming in the Control (0 kg N) and finishing in 675 kg N ha⁻¹ year⁻¹ (Table 4.3). This analysis showed that the crop response to fertilizer was highest with an N application of 250 kg N ha⁻¹ year⁻¹, corresponding to a 28 kg of DM production per kg. N applied. However, Napier grass also showed that it will respond to a continuous increase in N fertilization with amounts as high as 600 kg N ha⁻¹ year⁻¹.

6.5 Model evaluation

The model evaluation was conducted with an independent of-experimental data set that was not used for model development. The experiment included two N inorganic fertilizer and two different cutting intervals and was discussed in detail in Chapter 3. The challenge of this evaluation was to achieve a close relation between new and enhanced technologies and farmers' practices, in order to generate an effective tool for technology transfer and adoption, the final goal for long-term sustainability.

The main objective of this study was to evaluate the model for predicting development, aboveground biomass production, plant height, number of leaves per stem and the nitrogen concentration of Napier grass under a cut and carry system.

The crop model accurately predicted above-ground biomass for both the 30 and 60-days cutting interval, but, it shows lesser precision for the last two harvests. Model performance was fairly accurate, because the model was evaluated for four different seasons and two cutting intervals that included an impact of repeated plant measurements. In general the model seemed to perform better during the Fall and Winter seasons. It also performed better in predicting growth of young Napier grass plants compared to older and established Napier grass plants.

Similar to biomass prediction, the model had some difficulties with predicting leaf number per stem for the second part of sampling period, where the growth and development dynamics of the plant were reactivated by an increase in temperature.

Plant height was cut back to a few growing points and was reduced to the height at which the crop was cut at each harvest. This can be clearly seen in Figure 5.6 where simulated plant height was not adequate reduced, especially for the final three harvests. Further modifications to the model might be required so that it can handle multiple crop harvests.

The prediction of the nitrogen concentration in leaves, stems and total aboveground biomass was not clearly defined by the model, because it is important to consider that N concentration is different from a forage grass when compared to an annual crop. For an annual crop the physiological processes terminate when

physiological and harvest maturity are predicted, while the model calibration treated that in the forage grass the nitrogen concentration might decrease at the time when the cut takes place, but then increases significantly with new growth and supplemental fertilizer after harvest. This will require somewhat different nitrogen dynamics, although the model showed a very strong response to the nitrogen fertilizer application after each cut (Figures 5.7 and 5.8).

6.6 Proposal for application of the model as a decision support tool

The main goal of this thesis was to develop a Napier grass model that can predict crop performance based on weather and soil conditions and soil fertilizer requirements. Furthermore, one of the final objectives was to generate an intermediate solution for smallholder dairy farmers to improve their forage production under cut and carry system.

The use of animal manure as an additional resource to increase production of Napier grass and to maintain soil fertility is an option for smallholder systems, which due to the economic limitations are forced to base its milk production on the forage production of the farm. Therefore, Napier grass was characterized from the point of view of biomass production and plant structural characteristic as discussed in Chapter 2. The results showed that there are important advantages in recycling cow manure. However, the use of this organic fertilizer needs to be integrated in the Napier grass model. Its inclusion will allow for the generation of many options using manure alone as fertilizer resource or mixing it with inorganic fertilizers.

Another option to manage Napier grass as a forage resource is using inorganic N fertilizer, but considering NUE, NRE and the grass productivity to evaluate its economic justification and significance. One of the objectives of this study was to determine how much the crop is affected by the cold season, especially low temperatures, as farmers know the daily forage requirement for livestock and how much Napier grass should be produced in order to cover the intake of dairy cows. The outcomes of this study will apply more to medium and large dairy systems, as these farmers have access to irrigation systems and inorganic fertilizer.

The overall goal of agricultural science is to directly or indirectly improve the economic sustainability of farmers. The farmer's economic sustainability is based on his or her net income, which is directly a function of total production. Plant growth models can play a critical role in the effort to maintain the economic sustainability of farmers, as well as protecting our natural resources. The crop simulation models can be used to provide farmers with alternate options that can increase production and ultimately net income. It can also be used by researchers to determine research gaps and enhance research efficiency, in this case as it relates to Napier grass. While developing the Napier grass model, in general not much information was available with respect to the response of Napier grass to a wide range of environmental conditions, including temperature, and crop management scenarios.

Finally, the challenge is how to integrate the DSSAT program as a useful tool to improve the management of Napier grass crop in dairy systems. To implement these following recommendations are provided:

- To complement the calibration and evaluation of the Napier grass model with additional experimental data that represent different environments and different management scenarios, especially organic fertilizer.
- To promote the DSSAT program and especially its model-based outcomes to farmer governmental and non-governmental organizations that are developing technology transfer programmes. It will, therefore, be necessary to show the advantages of using a model to predict crop yield and soil conditions. In the tropical area of Bolivia, the agricultural systems are diversified (crop – livestock) and the many options of DSSAT, including more than 20 crops, including Napier grass, can provide new options for farmers for controlling and improving the crop-soil relation in order to obtain a long-term economic sustainability. However, it is not expected that farmers directly will use DSSAT. Rather, that simple decision support tools will be developed that are based on outcomes of DSSAT.
- Technicians are needed that are familiar with DSSAT and especially the Napier grass model. This should be supported by a handbook with the

agronomic characteristics of Napier grass and the minimum data requirements, for the model, including weather, soil and crop management. From a nutritional point of view, the nitrogen (protein) prediction of the model will not only help with the calculation of biomass prediction but can also define the forage N concentration in order to equilibrate the diet for lactating cows.

It is expected that the application of the Napier grass model as a decision support tool can ultimately benefit the resource poor farmer in Bolivia and other countries in South and Central America.

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